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Rainfall, Runoff and Soil Moisture under Desert Conditions

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Under arid conditions the character and seasonal distribution of the precipitation is more important than under moist ones, both with reference to its agency in remodeling the land surface and its rôle in supplying water for plant and animal life. The influence of rainfall on physiographic processes is direct and immediate, but its relation to the vegetation is through the medium of the soil and is therefore subject to a number of modifying circumstances. The study and interpretation of these involves all of the conditions that influence the fate of water from the time that it falls until it becomes available to the roots of the plant. The following pages embody the results of an investigation of some of the influences operative in a desert of the less pronounced type.

The digest of rainfall conditions is based on the record of the Desert Laboratory of the Carnegie Institution of Washington, at Tucson, Arizona, from 1905 to 1933. The investigation of runoff and soil moisture has been made on the part of the grounds of the Desert Laboratory which lies in the floodplain of the Santa Cruz River, and on the adjacent bajada soil.

The securing of the data on which this paper is based has required faithful and accurate work on the part of several of my associates. I wish here to express my gratitude to Dr. Robert R. Humphrey and Mr. William V. Turnage for their sustained interest in the often arduous work of soil sampling, and to Mr. Arthur L. Hinckley for his unremitting attention to the runoff readings and his careful supervision of the recording instruments.

The rainfall of the Tucson region is biseasonal and of the monsoon type. Its annual distribution closely resembles that of the Rajputana in India, with a strong summer maximum and a weaker winter maximum. In going west from Tucson the winter precipitation becomes relatively greater, while toward the east and south a greater percentage falls in the summer. In general the summer rains are torrential thunderstorms and the winter ones gentle and prolonged, but there are frequent exceptions in both seasons.

RAINFALL

The record of precipitation at the Desert Laboratory was begun June 1, 1904, but the preservation of the records of individual daily readings was not begun until January 1, 1907. All readings since that date are from the same spot in an enclosure near the laboratory buildings at an elevation of 2670 ft. (815 m.), on a shoulder of Tumamoc Hill. The location overlooks the floodplain of the Santa Cruz River and is 335 ft. (102 m.) above it. The basal area of Tumamoc Hill is approximately 1.3 sq. mi. and its summit is 775 ft. (236 m.) above the surrounding plain. Precipitation is measured in a gauge of the smaller standard type in use by the United States Weather Bureau, with funnel 3 in. in diameter. The instrument is placed on the ground at a distance of 50 ft. from the nearest building. Readings are made after each rain.

The average annual rainfall at the Desert Laboratory for the 29 years from 1905 to 1933 is 12.79 in. (325 mm.). The average for the same period for the city of Tucson, based on readings taken 4 miles from Tumamoc Hill, is 11.91 in. (303 mm.). The variability of the total from year to year is indicated in Fig. 1, the highest being 23.32 in. (592 mm.) in 1905 and the lowest 5.84 in. (148 mm.) in 1924. In 14 of the 29 years the total ranged from 10 to 14 in. The greatest single daily fall was 5.01 in. which is 86% of the lowest annual total.

The monthly distribution of precipitation is shown in Table 1. The summer rainy period is rather sharply limited to July, August, and the first two weeks of September. Occasionally the first heavy summer rain falls late in June, raising the average or that otherwise very dry month. For the first 25 days of June the average for the 27-year period is only .24 in. while for the entire month it is .46 in. The continuance of the rains into September is responsible for raising the average of a month the last half of which is usually very dry. The winter rainy season is poorly defined and variable from year to year. It may commence late in November and may continue as late as the middle of March. The maximum of the winter fall is usually in December but sometimes occurs in January. The variability

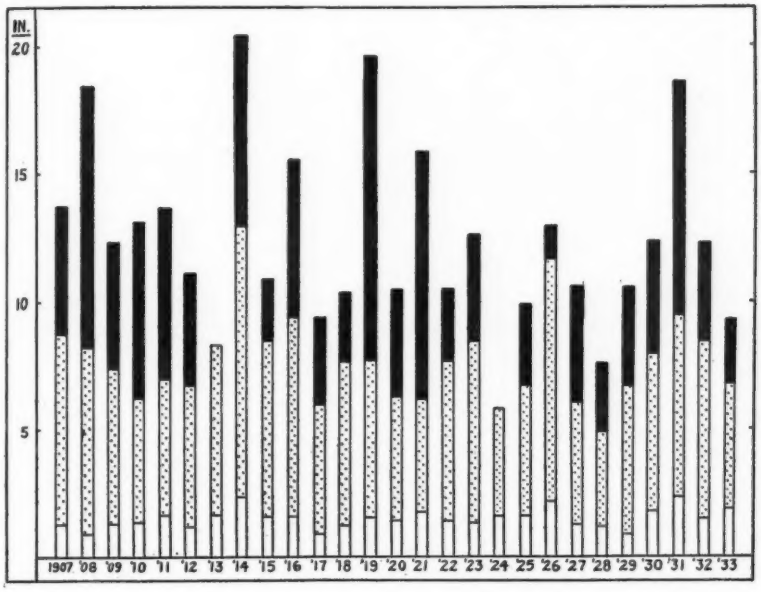


FIG. 1.—Annual rainfal at Desert Laboratory, Tucson, Arizona, from 1907 to 1933, showing amounts of annual totals derived from rains less than .15 in. (white), between .15 and .75 in. (dotted) and over .75 in. (black).

TABLE 1

RAINFALL, DESERT LABORATORY, TUCSON, ARIZONA. AVERAGE MONTHLY RAINFALL AND GREATEST AND LEAST MONTHLY FALL FOR THE YEARS 1905 TO 1933

	Average	*Highest*	*Lowest*
January	.86	3.94	.00
February	.93	4.11	.00
March	.80	4.27	.00
April	.46	3.11	.00
May	.21	1.10	.00
June	.46	2.59	.00
July	2.90	7.33	.90
August	2.16	4.44	.26
September	1.35	4.54	.06
October	.59	2.83	.00
November	.93	4.52	.00
December	1.14	6.14	.00
Total	12.79	—	—

of the monthly rainfall is indicated in Table 1, in which the highest and lowest readings for each month are given for the 29-year period. The highest falls for July and December have exceeded the lowest annual total. All months except July, August, and September have at times been rainless, May and June on 6 years and November on 8 years of the period.

The year is distinctly divided into two rainy periods and two dry ones, whatever variation in time they may happen to exhibit from year to year. Separation on a monthly basis is far from satisfactory, but the humid winter may be roughly taken as including December, January, February, and March, the arid spring April, May, and June, the humid summer July, August, and September, the arid autumn October and November. The totals by years for the four seasons are shown in Table 2, the figures used for December being those of the preceding year. The summer rains form 50.0% of the annual total, and those of winter 29.5%, leaving 8.7% in the arid spring and 11.8% in the arid autumn. If the limits of the seasons were shifted from year to year to conform to the variation in their time there would be considerable reduction in the percentages for the arid seasons.

The irregularity of the rainfall in southern Arizona, and in all desert regions, greatly increases the adverse character of the conditions for plants. There is little relation between annual rainfall totals and the amount of moisture in the soil. If a rainfall of 1.20 in. falls in a single shower, in four rains of .30 in. or in 12 showers of .10 in. the effect on the moisture of the soil and on vegetation will be different in each case. In the first there will not ensue a penetration of water into the soil much greater than in a shower of one third the amount, the remainder running off to the streamways. In the last case there will be only a very superficial wetting of the soil, unless it happens that the showers of .10 in. follow in rapid succession or fall on cool cloudy days.

An inspection has been made of the daily entries in the Desert Laboratory record with a view to making a rough separation of the rains into the heavy ones which are accompanied by active runoff, the light ones insufficient to raise the soil moisture, and the intermediate, or effective, rains in which there is little or no runoff and a good penetration of water into the soil. In work with three types of soil it has been found that rains of less than .15 in. (4 mm.) are without influence on soil moisture at 15 cm., unless this amount falls on a surface which is already moist and is followed by cloudy weather. The amount of rain required to produce runoff is extremely variable, as will be shown, and an arbitrary limit of .75 in. (19 mm.) has been placed as the minimum for rains which are usually productive of runoff. Fig. 1 shows the annual rainfall totals and indicates the

amount of light, effective and torrential rain in each year. There is considerable variation in the relative and absolute amounts of the three classes.

TABLE 2

RAINFALL, DESERT LABORATORY, TUCSON, ARIZONA. SEASONAL DISTRIBUTION 1905 TO 1933. WINTER TOTALS INCLUDE DECEMBER OF THE PRECEDING YEAR

Year	*Winter* *Dec., Jan., Feb., Mar.*	*Spring* *Apr., May, June*	*Summer* *July, Aug., Sept.*	*Autumn* *Oct., Nov.*
1905	11.36	3.38	4.18	4.57
1906	3.07	.36	3.51	.67
1907	7.36	.45	8.61	1.69
1908	3.08	.19	12.04	.59
1909	3.85	.58	8.67	.97
1910	1.91	.38	9.99	1.42
1911	2.34	.29	8.98	1.45
1912	3.30	.87	6.73	.64
1913	3.09	.59	2.03	1.91
1914	3.13	1.64	6.52	3.97
1915	9.61	.63	3.74	.85
1916	7.63	.68	7.15	1.48
1917	2.99	.79	6.36	.00
1918	2.81	.99	3.18	1.77
1919	3.43	2.16	11.35	3.82
1920	5.06	1.57	3.74	.41
1921	.91	1.21	13.10	.75
1922	2.10	2.81	5.21	.45
1923	1.15	.41	5.96	2.99
1924	3.68	.62	2.31	.72
1925	.97	1.20	5.28	2.89
1926	3.43	2.01	4.41	1.37
1927	4.30	.73	6.01	.37
1928	2.16	.11	5.04	.93
1929	1.85	.72	8.27	.00
1930	4.90	2.81	3.67	1.11
1931	3.87	3.61	7.65	3.32
1932	3.10	.34	5.55	1.69
1933	3.13	.26	6.46	1.28
Average	3.77	1.11	6.40	1.51
Per cent of total	29.5	8.7	50.0	11.8

In 1913 and 1924 the annual total was low and there were no torrential rains. In the wet years 1908, 1919 and 1921 the torrential rains yielded more than half of the annual total. In the dry years 1917 and 1928 the torrential rains still yielded one third of the annual total. The light rainfall is relatively uniform from year to year, generally being more in its absolute and less in its relative amount in the wet years. In the dry year 1924 the light rains were one fourth of the annual total. Inspection of the graph in Fig. 1 brings out the fact that there is a greater uniformity in the effective rainfall than in the total, and that the wet years differ from those of low or moderate rainfall largely in the amount of torrential rain by which they are visited.

In more pronounced deserts it appears to be true that the irregularity of the rainfall is greater than at Tucson, and that the percentage of the total which falls in torrential showers is much greater. Indeed some of the driest localities for which there are records have gone for periods of several years without rain, only to be visited at rare intervals by heavy downpours.

A more detailed separation of the individual rains into intensity classes has been made, and the totals yielded by them are shown in Table 3. The highest total yields are for the lowest classes, in which the frequency is greatest, and there is an irregularly progressive decline until the highest class is reached. Marked variability is exhibited here, as in all other aspects of the rainfall conditions.

The number of rainy days has also been tabulated with reference to the intensity classes into which their yields fall (Table 4). The number of rainy days ranges from 31 to 58 per annum, the average being 45.5. It may be noted that there is only one day in every 158 on which a rain of 1 in. or more takes place.

DROUGHT PERIODS

A feature of the rainfall conditions which is of great importance to plants is the frequency and duration of the periods in which precipitation is absent or not great enough to affect the moisture of the soil. The duration to which a period must attain in order to be considered a drought period is a matter of arbitrary selection. In the warm months a period of two or three weeks without rain will kill the herbaceous ephemeral plants and will check the activity of the root perennials and small shrubs. On the other hand a period of two or three months without precipitation will be of little consequence to cacti and such deep-rooted trees as the mesquite (*Prosopis*) and catclaw (*Acacia greggii*).

As stated above it has been found that rains of .15 in. or less are without

TABLE 3

RAINFALL, DESERT LABORATORY, TUCSON, ARIZONA, AMOUNTS OF PRECIPITATION YIELDED BY RAINY DAYS GROUPED IN INTENSITY CLASSES

Year	.01 to .25	.26 to .50	.51 to .75	.76 to 1.00	1.01 to 1.25	1.26 to 1.50	1.51 to 1.75	1.76 to 2.00	2.01 to 2.25	2.26 to 2.50	2.51 to 2.75	2.76 or over
1907	2.64	2.89	3.24	1.00	2.38	...	1.56	...	...	...	...	...
1908	1.93	3.26	3.07	4.52	1.20	...	...	1.83	...	...	2.60	...
1909	2.62	3.20	1.66	...	3.44	1.40	...	...	...	...	...	...
1910	1.81	1.74	2.68	1.81	...	...	...	...	...	...	...	5.01
1911	3.29	2.29	1.56	5.16	...	1.42	...	...	...	...	...	...
1912	2.67	3.44	.69	1.73	1.12	1.48	...	...	...	...	...	...
1913	3.62	2.72	1.95	...	...	...	...	...	...	...	...	...
1914	3.27	4.93	4.73	.82	1.04	4.05	1.53	...	...	...	...	...
1915	2.83	2.34	3.43	.79	...	...	1.52	...	...	...	...	...
1916	2.63	2.96	3.87	...	3.54	...	...	...	...	2.50	...	...
1917	2.72	2.69	.66	.84	1.10	1.35	...	...	...	...	...	...
1918	2.73	1.80	3.11	2.73	...	...	...	...	...	...	...	...
1919	2.83	2.47	2.45	1.84	5.47	2.75	...	1.85	...	...	...	...
1920	3.24	2.59	.55	.92	3.21	...	...	...	...	...	...	...
1921	3.40	1.59	1.21	1.86	2.11	...	1.75	1.87	2.14	...	...	...
1922	2.32	4.70	.62	.81	2.08	...	...	...	...	...	...	...
1923	3.37	3.88	1.27	1.63	1.01	1.45	...	...	...	...	...	...
1924	2.37	2.13	1.34	...	...	...	...	...	...	...	...	...
1925	3.04	2.70	1.07	.95	2.17	...	...	...	...	...	...	...
1926	3.17	3.29	5.24	...	1.24	...	...	...	...	...	...	...
1927	3.13	2.21	.75	1.71	...	2.78	...	...	...	...	...	...
1928	1.20	2.60	1.15	1.61	1.06	...	...	...	...	...	...	...
1929	2.25	3.34	1.19	.80	...	...	...	...	...	...	...	2.99
1930	2.78	3.39	1.84	...	4.41	...	...	...	...	...	...	...
1931	3.78	3.11	2.75	2.78	1.03	1.30	...	1.88	2.05	...	...	...
1932	2.28	3.62	2.59	2.69	1.12	...	...	...	...	...	...	...
1933	2.83	2.21	1.79	...	1.05	1.42	...	...	...	...	...	...
Totals	73.75	78.09	56.46	37.00	39.78	19.40	6.36	7.43	4.19	2.50	2.60	8.00
Averages ...	2.73	2.89	2.09	1.37	1.47	.72	.24	.28	.16	.09	.10	.30

influence on the moisture of the soil at 15 cm. A length of 30 days has been selected as constituting a drought period of mean duration with respect to plant activity, and the periods have been calculated without reference to rains of .14 in. or less. The distribution of such periods for the past 27 years is shown in Fig. 2. There have been from 2 to 5 drought periods annually, or a total of 94 periods, together constituting 55% of the elapsed time for the years covered. The longest period was 149 days, extending from Feb. 16 to July 13, 1928. There have been 8 periods of more than 100 days, and 24 periods of 70 days or more. Inspection of Fig. 2 shows the prevalence of drought during April, May and June and its frequence

TABLE 4

RAINFALL, DESERT LABORATORY, TUCSON, ARIZONA. NUMBER OF RAINY DAYS GROUPED IN INTENSITY CLASSES

Year	T	.01 to .25	.26 to .50	.51 to .75	.76 to 1.00	1.01 to 1.25	1.26 to 1.50	1.51 to 1.75	1.76 to 2.00	2.01 to 2.25	2.26 to 2.50	2.51 to 2.75	2.76 or over	Total without T
1907	18	28	8	5	1	2	..	1	..	..	..	..	..	45
1908	9	25	8	5	5	1	..	..	1	..	..	1	..	46
1909	21	33	8	3	..	3	1	..	..	..	..	..	..	48
1910	16	24	5	4	2	..	..	..	..	..	..	..	1	36
1911	22	33	7	3	6	..	1	..	..	..	..	..	..	50
1912	19	27	9	1	2	1	1	..	..	..	..	..	..	41
1913	18	36	8	3	..	..	..	..	..	..	..	..	..	47
1914	23	33	13	8	1	1	3	1	..	..	..	..	..	60
1915	21	27	7	6	1	..	..	1	..	..	..	..	..	42
1916	8	30	8	6	..	3	..	..	..	..	1	..	..	48
1917	7	25	7	1	1	1	1	..	..	..	..	..	..	36
1918	28	28	5	5	3	..	..	..	..	..	..	..	..	41
1919	21	34	7	4	2	5	2	..	1	..	..	..	..	55
1920	17	31	7	1	1	3	..	..	..	..	..	..	..	43
1921	22	34	4	2	2	2	..	1	1	1	..	..	..	47
1922	19	27	13	1	1	2	..	..	..	..	..	..	..	44
1923	18	32	12	2	2	1	1	..	..	..	..	..	..	50
1924	12	23	6	2	..	..	..	..	..	..	..	..	..	31
1925	11	36	7	2	1	2	..	..	..	..	..	..	..	48
1926	26	40	9	8	..	1	..	..	..	..	..	..	..	58
1927	8	33	6	1	2	..	2	..	..	..	..	..	..	44
1928	12	19	7	2	2	1	..	..	..	..	..	..	..	31
1929	15	22	10	2	1	..	..	..	..	..	..	..	1	36
1930	*	37	9	3	..	4	..	..	..	..	..	..	..	53
1931	*	37	8	4	3	1	1	..	1	1	..	..	..	56
1932	6	24	11	4	3	1	..	..	..	..	..	..	..	43
1933	13	38	6	3	..	1	1	..	..	..	..	..	..	49
Totals	410*	816	215	91	42	36	14	4	4	2	1	1	2	1228
Averages	15.2	30.2	7.9	3.4	1.6	1.3	0.5	0.1	0.1	..	..	..	..	45.5

during October and November. It is uncommon for the drought-free condition of midsummer to be as brief as it was in 1913, or for a drought period to begin in July or August, as happened five times. The distribution of drought periods emphasizes the irregular incidence of the winter rains as compared with those of the summer.

There are 22 cases in which drought periods are separated by a single rainy day, and one case in which two rainy days intervened. Some of the mid-drought rains were light, 7 being less than .30 in. (8 mm.), while some of them were heavy, 6 being .60 in. (15 mm.) or more. These cases are naturally most frequent in the normally dry periods, 13 of them having occurred in April, May, and June and 5 in October and November. What-

ever may be the amount of a rain which falls on very dry soil and is succeeded by clear days and high temperature for a period of more than 30 days, the benefit of such a fall in replenishing the moisture of the soil is

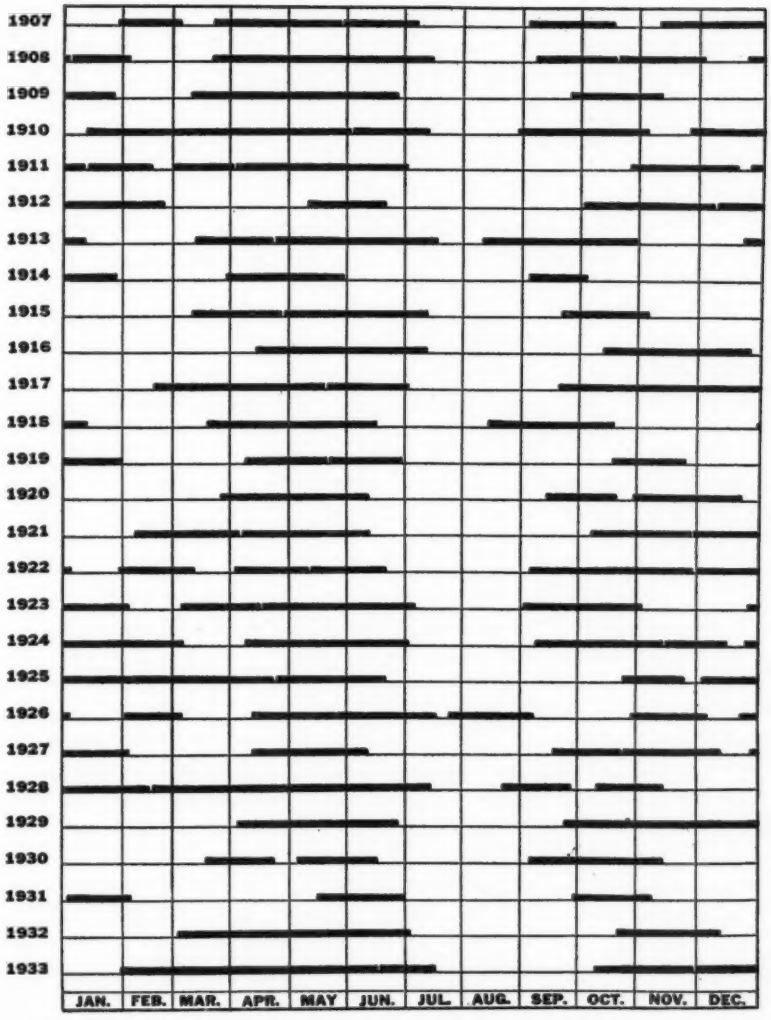


FIG. 2.—Incidence of rainless periods of 30 days or more at the Desert Laboratory, 1907 to 1933.

relatively small. Also the response of vegetation to the heaviest mid-drought rains is commonly confined to a slight renewal of activity on the part of small perennials which border the streamways. In short, many of the drought periods separated by a single rainy day are practically continuous, increasing the length of some of them to more than 6 months.

In considering the relation of drought periods to plants it must be remembered that their effect is cumulative. If a given amount of damage has resulted from a drought of 10 weeks, twice as much harm may be done to the perennial plants if the period lasts 2 weeks longer.

RUNOFF

Under desert conditions runoff is greater in its amount and more important in its consequences than in moist regions. Heavy rains of brief duration place water on the soil more rapidly than it can penetrate. In all soils of fine texture the dryness of the surface causes "puddling" as soon as the rain begins, and the penetration of water may advance only a few millimeters by the time the rain is over. Active evaporation quickly removes moisture from the superficial layers of the soil. The fact that the ground is bare or only sparsely covered with vegetation aids the flow of the runoff and accelerates its movement into small drainageways and thence into the larger ones. The ready runoff is responsible for the "flash floods" which fill desert streamways with short-lived torrents. The runoff and the floods are responsible for the active erosion which has become a serious menace to the maintenance of grazing ranges and even the open types of forest in the southwestern states.

It is obvious that the amount of runoff is determined by a number of conditions. The most important is the intensity of the rain by which it is initiated. Almost equally important are the features of the surface on which it falls, notably the degree of slope, the texture of the soil, the nature and density of the vegetation, the amount of litter or stones on the surface, and the moisture of the soil surface. Rain which runs off a hill may penetrate the soil when it reaches a plain, and that which runs off the plain may penetrate the bed of the stream in which it is carried. In the desert it often happens that streams do not deliver their water to a consecutive system which reaches the sea but spread it over extensive playas where the water finally penetrates the soil. Thus do the plants of one locality depend on the rain which falls there while the plants of other localities have their local supply of water augmented by the runoff from elsewhere. The strongly contrasting types of vegetation found in the southwestern deserts are to be explained largely on the basis of differences in soil moisture which are in turn due to these circumstances.

In the spring of 1929 preparations were begun for the construction of an appliance which would make it possible to determine the amount of runoff from a small area and to measure any water which might penetrate the upper layers of the soil. A locality was selected in the flood plain of the Santa Cruz River, 2 km. from the bed of the river and 300 m. from the base of Tumamoc Hill. The soil is "adobe," a fine textured dark gray alluvial clay, free of stones and with a depth of at least 20 m.

The requirements suggested construcing a device similar to the lysimeters in use at the Rothamstead Experiment Station, enclosing an undisturbed body of soil with appropriate arrangements for reading both runoff and percolation. As the aim was the study of runoff and percolation rather than leaching the appliance was dubbed a "percolimeter." The essential features of its design may be seen in the horizontal plan and two sections shown in Fig. 3. Operations were begun by trenching around a body of

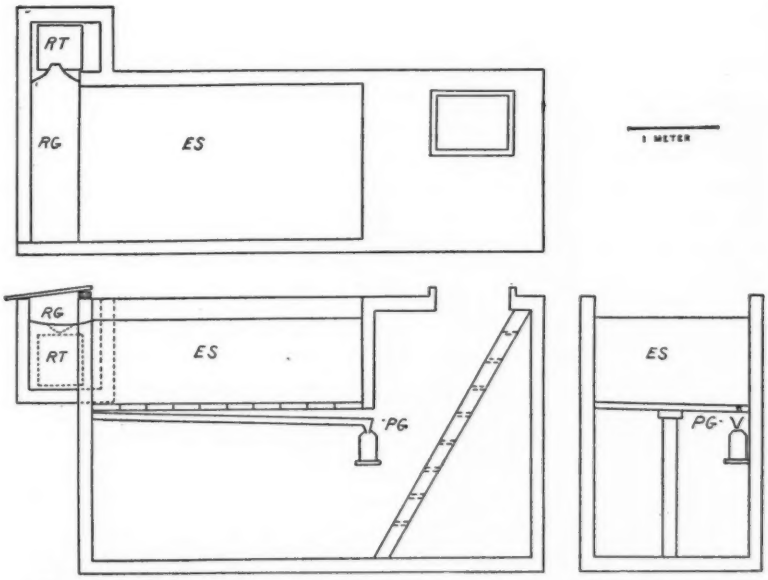


FIG. 3.—Horizontal and vertical sections of Percolimeter, designed for measurement of runoff and penetration of rain. ES = encased soil, RG = runoff gutter, RT = runoff tank, PG = percolation gutter.

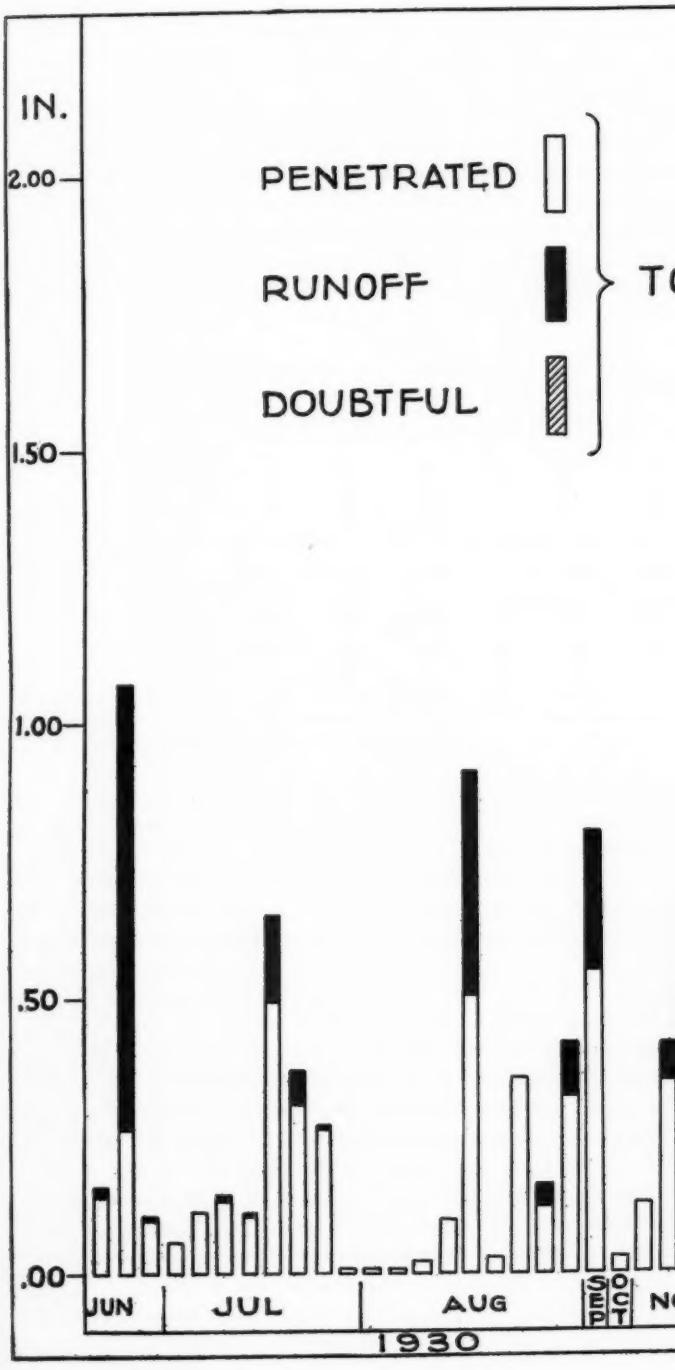
soil 3.1 by 1.7 m. in area and 1 m. in depth and filling the trenches with cement. A cellar was then dug to provide a means of entering for removal

of the soil under the encased block. As removal proceeded redwood boards 2 in. thick were put in place one by one so as to form a platform underlying the entire encased block. Cement walls were then made so as to line the cellar and support the redwood boards, to which additional wooden supports were given down the center of the block. The boards were grooved on top and placed with a slight dip to one side of the block. At their lower ends several holes were made in each board, so as to bring all of the holes in a line 3 cm. from the side of the cellar. Under the row of holes a metal gutter was placed leading to a large container. The cellar was subsequently provided with a cement roof, trap door and ladder.

The wall enclosing the block of soil was brought 10 cm. above the ground level on three sides. At one end it was brought up to the ground level and outside it a shallow cement gutter was laid, leading to a pit 60 by 100 cm. in area and 100 cm. deep. The end of the gutter was tapered and provided with a metal spout. In the pit was placed a large vessel to catch the runoff. The surface of the encased soil is kept level and free from weeds. The gutter is kept free of deposited soil and wind-blown leaves. On the roof of the cellar a tipping-bucket recording rain gauge is installed together with a gauge of the standard Weather Bureau type. The runoff vessel is examined after every rain and the volume of runoff calculated from the depth of the water in the vessel. Rains resulting in more than 1 in. of runoff fill the vessel, which is then bailed out and refilled with the water which has overflowed into the water-tight cement pit in which the vessel rests. A reading can then be made of the volume of the supplementary runoff. On June 30, 1931, 1.65 in. of rain (42 mm.) fell in 25 minutes, and in the same year there were two other violent rains of more than 1.50 in. (38 mm.). Each of these developed unforeseen defects in the percolimeter and the provisions for its protection from the sheet floods originating on the adjacent hill. It has been necessary to estimate the actual amount of runoff on these three occasions.

The graphs of rainfall made by the electric recorder are checked by measurement of the rain which accumulates in the container beneath the tipping bucket, since it has been found that the recorder usually shows a slight lag in very rapid rains. The readings made by graduated stick in the accompanying rain gauge of the standard type often show a difference from the readings of the tipping bucket gauge, as is invariably the case when gauges of different types are employed. In such cases the reading of the standard gauge is used.

The readings of runoff are converted into terms of the depth at which the given volume of water would stand if spread over the surface of the encased soil. This makes it possible to represent graphically the portion of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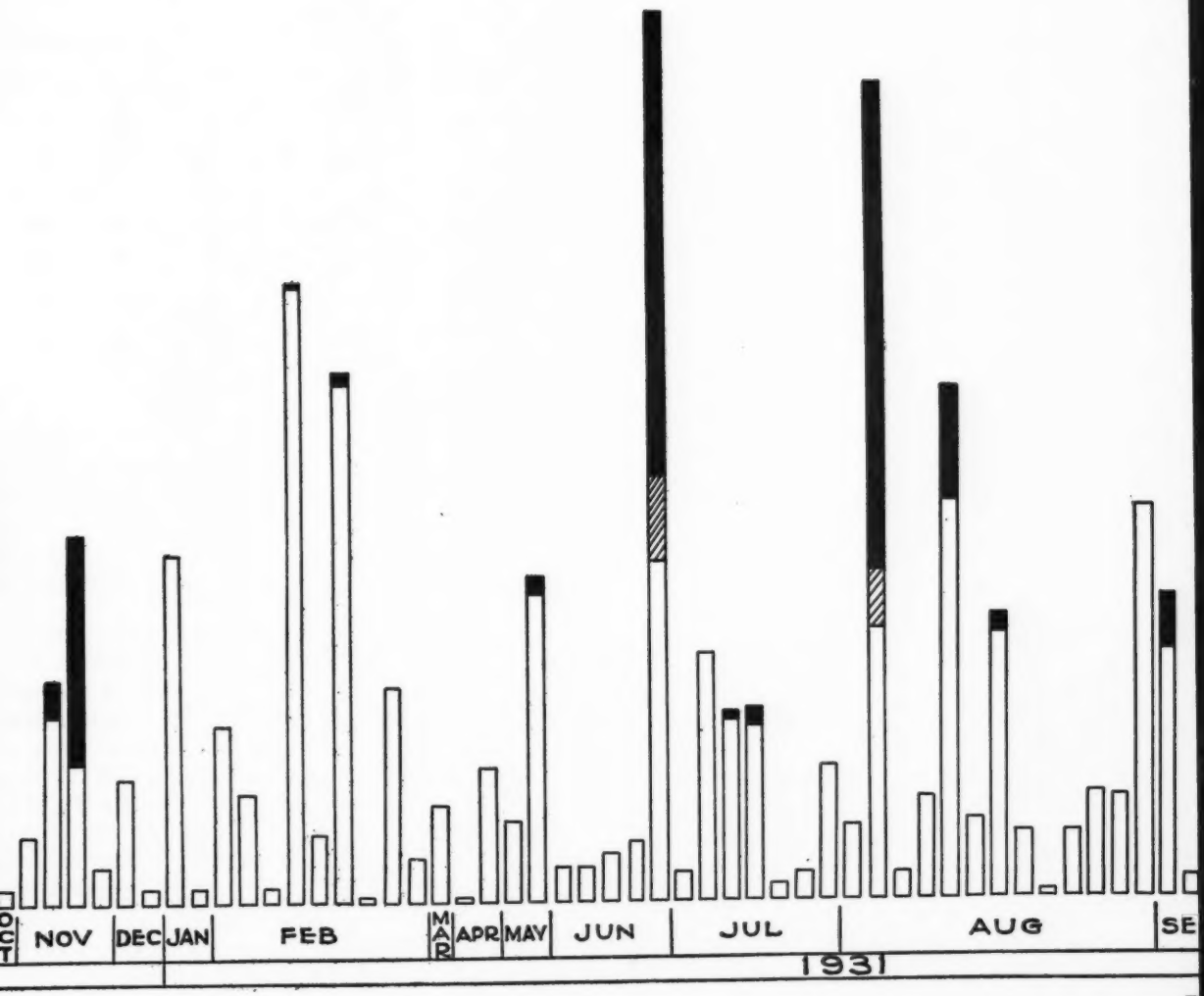
1930

TOTAL RAINFALL



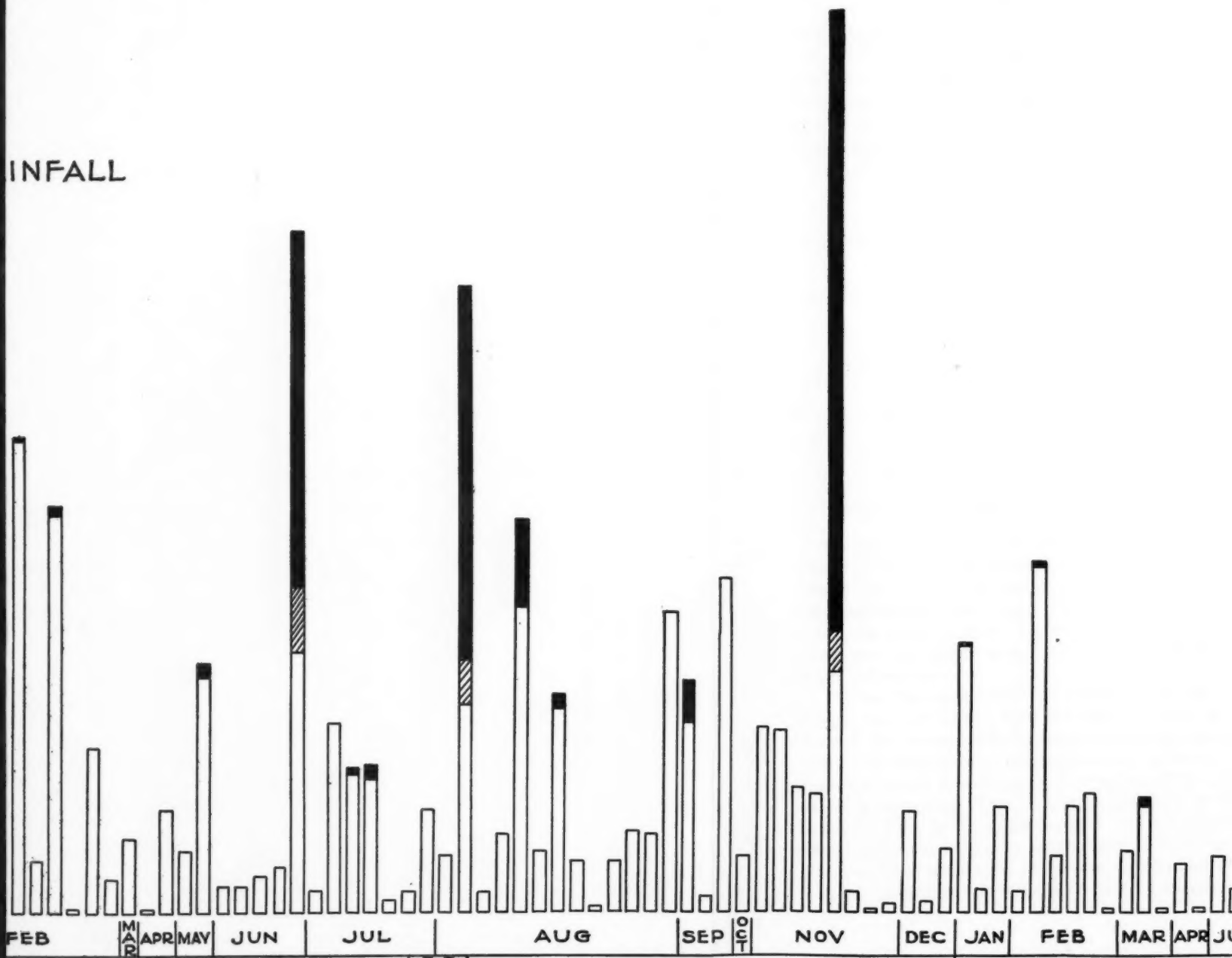
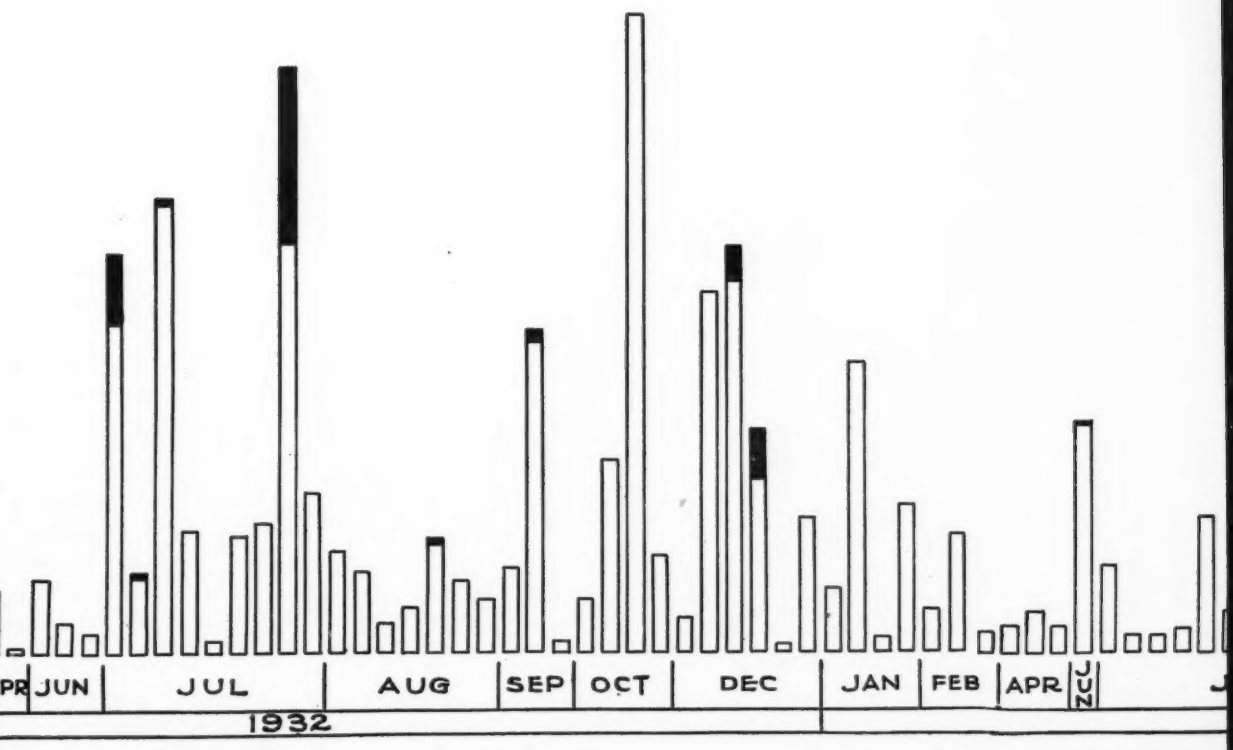
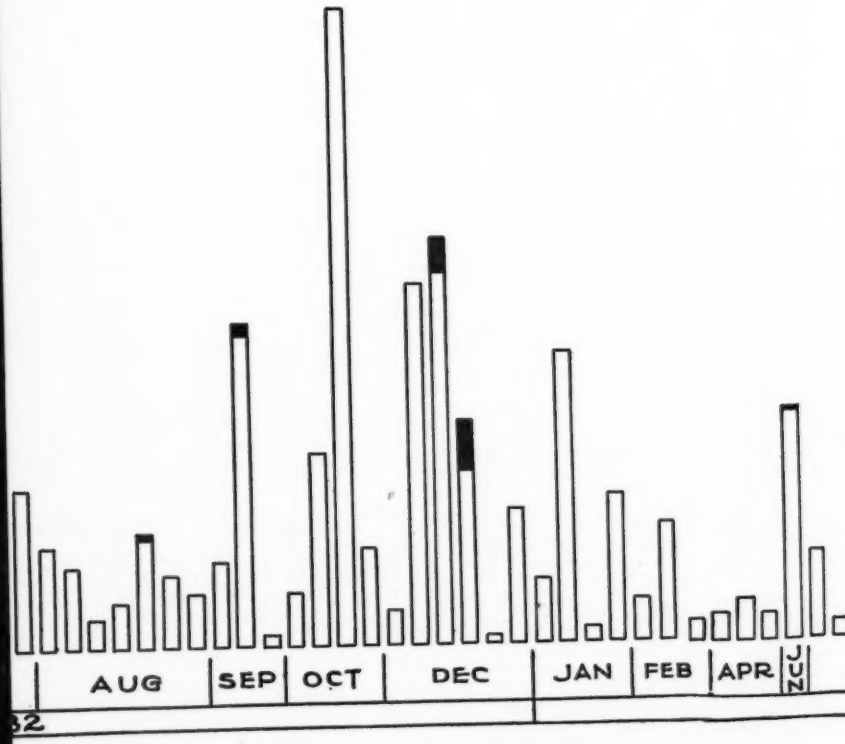


FIG. 4.—Amount of all rains from June, 1930, to December, 1933, and amount

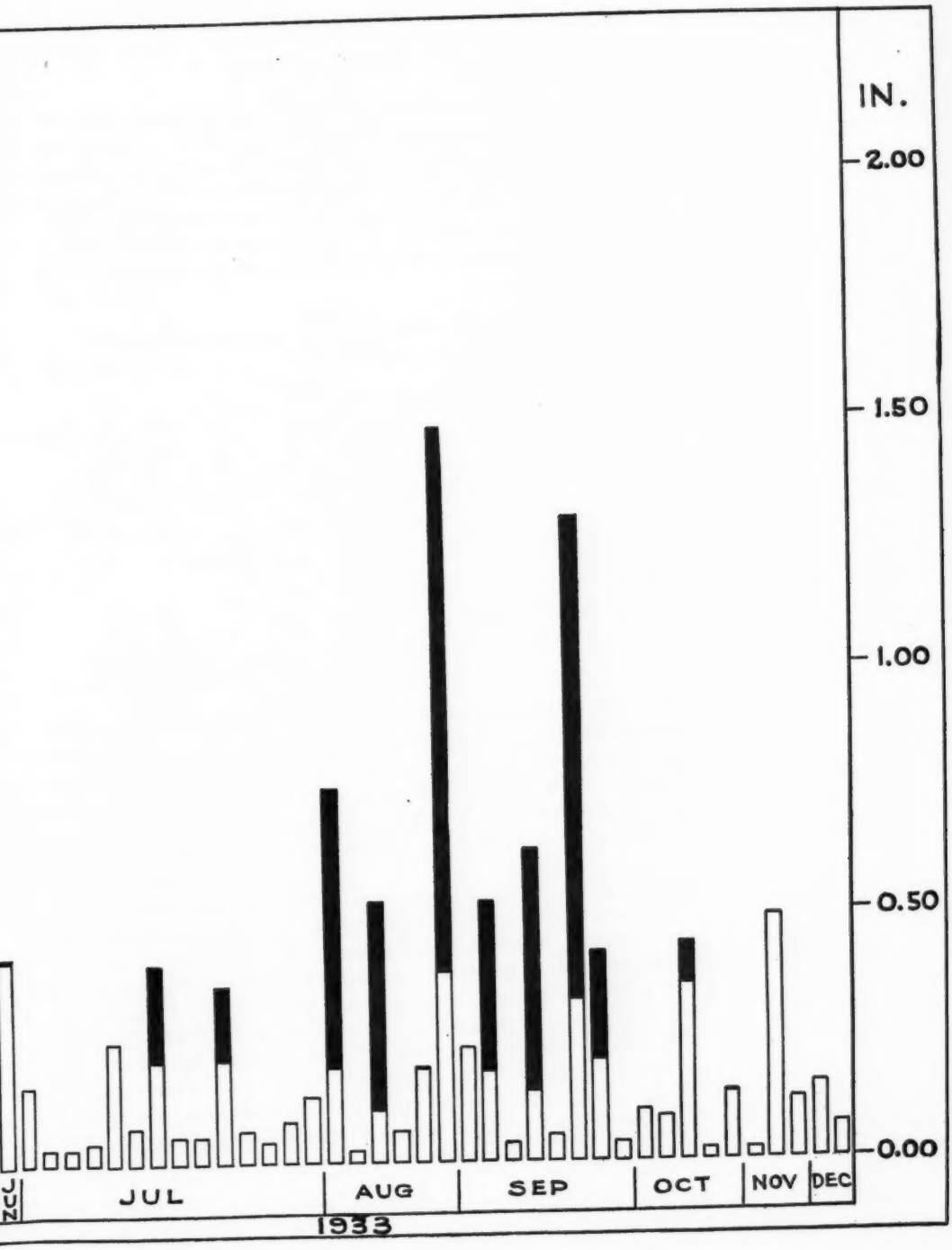


Amount of runoff (black) in each rain.



32

rain.


IN.
2.00
1.50
1.00
0.50
0.00
JUL
AUG
SEP
OCT
NOV
DEC
1933

each rain which penetrates the soil and the portion which runs off, as has been done in Fig. 4. In this figure the amount of each rain over .03 in. has been shown for the period of 3½ years, and the data have been arranged in consecutive series without reference to the number of intervening rainless days. The total height of each block indicates the total rainfall, and the black part indicates the amount of runoff as converted into terms of inches of water for the surface of the encased soil in the percolimeter.

TABLE 5

GENERAL RUNOFF DATA FOR THREE AND ONE HALF YEARS

Period	Number of rains	Rains with runoff	Rainfall			Runoff			Per cent of runoff
			Winter*	Summer	Annual	Winter*	Summer	Annual	
June–Dec. 1930	28	14	...	5.88	7.52	...	1.58	2.08	27.6
1931	56	11	4.49	9.87	19.37	.01	2.10	3.44 ±	17.7
1932	46	11	3.45	5.72	12.80	.05	.46	.65	5.0
1933	49	13	3.43	8.42	11.52	.14	4.45	4.53	39.3

* Winter includes December of preceding year.

The general features of the runoff record are indicated in Table 5. The number of rains providing runoff is from one half to one fifth of the total number over .03 in. The summer runoff is very much greater than that accompanying the winter rains. The runoff has varied from 5% to 39.3% of the total annual rainfall. Neither the amount nor the percentage of the runoff bears any relation to the total rainfall, nor to the seasonal rainfall of winter and summer.

The fact that winter rains are commonly prolonged and gentle, while summer rains are usually brief and heavy explains the small amount of runoff in the former season as compared with the greater amounts in the latter. The importance of the duration of a rainstorm in determining the amount of runoff is revealed by examination of the graphs made by the recording rain gauge. Two heavy rains took place in February, 1931, the former 1.15 in., the latter .99 in., with only traces of runoff. The first storm lasted from 6:30 p. m. on February 11 until noon on February 12, while the second lasted from 12:30 p. m. on February 14 until midnight of the 15th. In neither case was there a peak of intensity. On October 11,

1932, there was a rain of 1.15 in. which began at 5:15 p. m., was at first rather heavy, .49 in. falling in the first 20 min., then became lighter and terminated at 7:45 p. m. In this case there was no runoff in spite of the intensity of the first downfall, which was probably due in large part to the fact that the surface of the soil had been moistened by a rain of .36 in. on October 9. This rain consisted of preliminary showers of .09 in. at 12:10 to 12:20 a. m. and of .05 in. at 12:50 to 12:55 a. m., with the remainder falling between 1:45 and 2:55 a. m. The graphs of the sunshine recorder operated at the office of the Desert Laboratory, within 100 m. of the percolimeter, show that there were only 25 min. of sunshine on October 9, which lessened soil evaporation and gave opportunity for the penetration of this gradual rain, which was without runoff. Conditions were thus made more favorable for the penetration of the heavy shower which initiated the rain of 1.15 in. on October 11.

In December, 1932, there were three consecutive days of rain, yielding .66 in. on the 12th, .74 in. on the 13th, and .41 in. on the 14th, with no runoff on the first day, .06 in. on the second and .08 in. on the third. The storm began at 2:30 p. m. on December 12 and lasted until 10:25 p. m. on the 14th. On the 13th and 14th there were several periods of 15 to 25 minutes in which the fall was at the rate of .12 in. per hour, but during most of the storm the fall was less than .05 in. per hour and there were lulls of 3, 2, 4 and 2 hours, respectively without precipitation. The conditions were ideal for the penetration of the rain, and the small runoff on the second and third days was doubtless due to the brief periods of sharp acceleration in the rate of fall.

The importance of the duration of a rainstorm is further illustrated by comparison of the rain of .52 in. on August 9, 1933, and that of .49 in. on November 29, 1933, the first of which produced a runoff of .42 in. and the latter none. The August rain lasted 13 minutes and the November rain began at 9 a. m. and lasted until 5 p. m., being heaviest between 2:30 and 4:30 p. m. In such a case as the fall of .52 in. in 13 min. it appears that the dryness or moistness of the soil surface is of little importance in affecting the amount of runoff on a clay soil.

The rain of August 21, 1933, was 1.48 in. and produced a runoff of 1.09 in. This rain began at 5:20 p. m. and during the first 30 min. .94 in. of rain fell, after which the fall was more moderate until 8:55 p. m. On September 17, 1933, a rain of 1.30 in. produced a runoff of .97 in. This rain began at 8:25 a. m. and yielded .62 in. in the first 35 min. with additional sharp downpours at 10:00 to 10:15 a. m. and a more deliberate fall of .22 in. between 11:00 a. m. and 12:05 p. m.

The first heavy rain of the summer period is usually a thunderstorm of

relatively brief duration. Falling on a surface which has been thoroughly dried by two or three months of light and infrequent rain there is usually a heavy runoff from it. In 1930 the rain of 1.08 in. of June 18 yielded .81 in. of runoff. In 1931 the rain of 1.65 on June 30 yielded a very heavy runoff which was estimated at .85 in. with the possibility of a plus or minus error of .10 in. In 1932 the rain of .73 in. on July 2 yielded .11 in. of runoff. In 1933 the rain of .42 in. on June 16 yielded only .01 in. of runoff. Examination of the records for these four rains shows that the first two were of 35 and 45 min. duration, respectively, and the second two of 60 and 55 min., respectively. The intensity of these rains for the four years, respectively, was .031 in. per minute, .034 in., .012 in. and .007 in. All other conditions being the same in each case it would appear that the greater runoff in 1930 and 1931 and the smaller runoff in 1932 and 1933 must be attributed to the difference in the intensity factor.

With observations made on a single type of soil under uniform conditions of bare, level surface without vegetation it appears that the duration and intensity of the rainstorms are the most important factors determining the amount of runoff, with a very minor rôle played by the moistness of the surface at the time of the rain.

PERCOLATION

During the three and one half years of observation there has at no time been more than a trace of percolation through the encased block of soil. This has doubtless been due in great part to the provision for runoff from the surface of the block. In this respect the encased soil has been strictly comparable to the entire area of floodplain soil by which it is surrounded. Under present conditions water collects in pools after heavy rains in places where the surface has been disturbed by road building or other human activities. Under natural conditions all of the small depressions are quickly filled with soil carried by the runoff floods. It is probable that there are small areas in which the low gradient of the surface causes more penetration than took place on the surface of the encased soil. No moisture determinations have been made in the block in the percolimeter since it would have caused a disturbance of the natural structure of the soil.

The texture of the adobe clay makes it highly retentive of water. Its water holding capacity is 50.4% and water would be released by the capillary films of the soil and would respond to gravity only in case the moisture content exceeded this percentage. The weight of the encased block of soil has been estimated at 7272.6 K. A rainfall of 1 in. would place 134.38 L. on the soil surface, and if this penetrated the soil without loss, and became evenly distributed throughout it, would serve to raise the moisture content

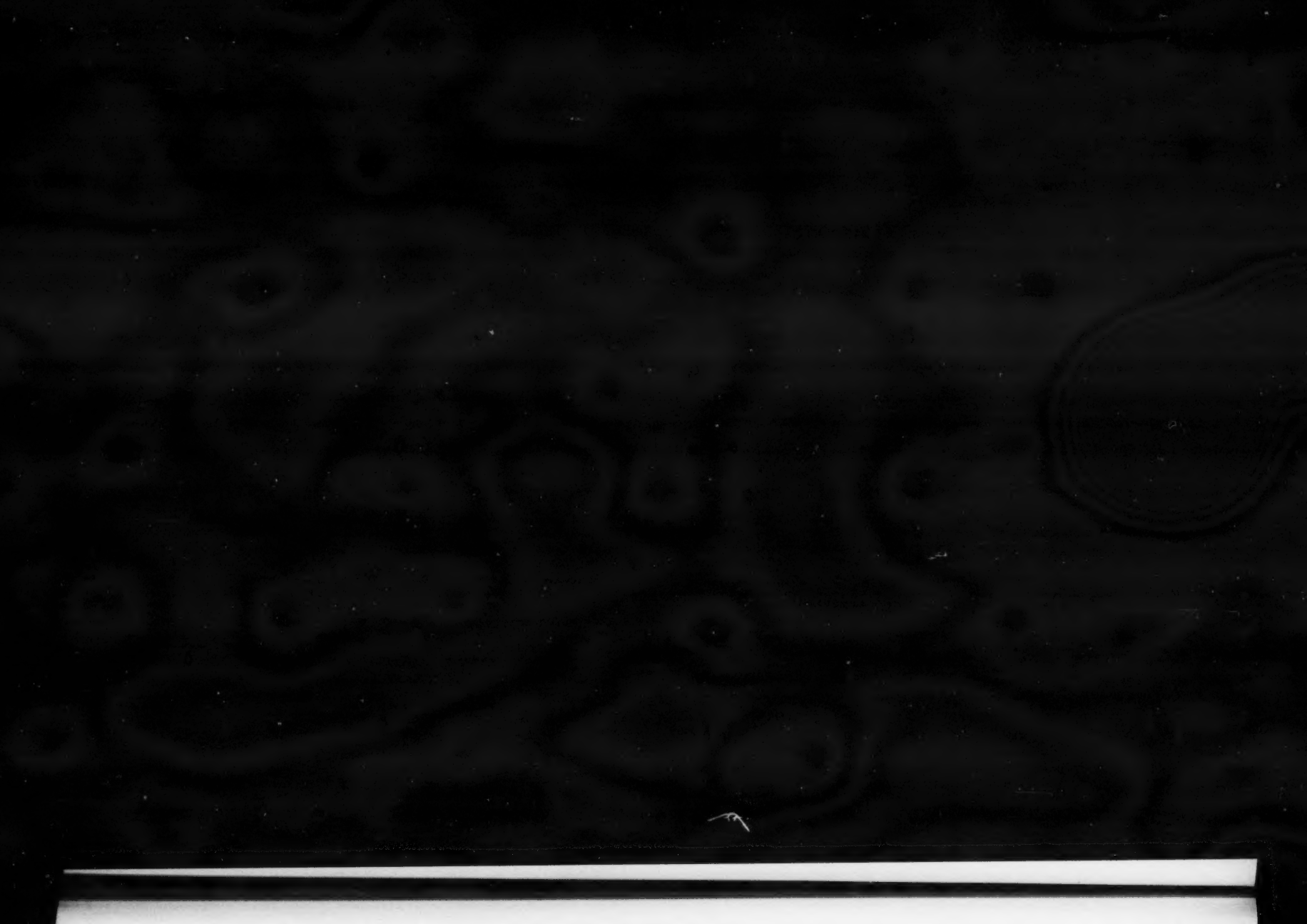
1.85%. The mean annual moisture of the adjacent soil from the surface to a depth of 1 m. is approximately 11%. Under average conditions the block therefore contains an amount of water which it would require 5.94 in. of rain to furnish. In order to raise the moisture of the entire block to 30% it would be necessary to have a rain of 16.21 in. at one time and without loss by runoff or evaporation. To raise it to 50.4% would require a rain of 27.22 in. under the same conditions. The reasons for the lack of percolation are therefore obvious.

SOIL MOISTURE

Since September, 1930, determinations of soil moisture have been made in the alluvial clay, or adobe, of the Santa Cruz floodplain at a locality 35 m. from the percolimeter. These have been made at fortnightly intervals at depths of 15, 30, 45, 60, 90, 120, 150 and 180 cm. In March, 1931, and March, 1932, determinations were also made at depths of 240, 300 and 360 cm. In April and December, 1933, readings were secured at depths of 210, 240, 270, 300, 330 and 360 cm. The relative constancy of the moisture at 150 and 180 cm. made it seem unnecessary to extend the fortnightly readings below the latter depth. The annual readings at the lower levels were taken at a time when it was believed that the maximum penetration of the winter rains had been reached.

In March and June, 1932, and in the same months in 1933 determinations of moisture were made in the loam soil of the bajada of the Tucson Mountains in the western part of the Grounds of the Desert Laboratory at depths of 15, 30, 45, 60, 90, 120, 150, 180, 210, 240, and 270 cm., the three lowest levels being omitted in the June readings. The dates of these determinations were selected to obtain the highest and lowest values for the year. In the floodplain it was possible to use a soil borer on account of the absence of stones. On the bajada it was necessary to make a fresh excavation with pick and shovel for each set of determinations, requiring the labor of two men for two days. Here again there is a fair degree of constancy in the lower levels.

All samples were placed immediately in sealed jars, weighed and dried in the customary manner and the amount of moisture calculated on the basis of dry weight. On the floodplain each boring was made at a distance of 2 m. from the last one until ten borings had been made in a straight line, when another series in a parallel line was taken in reverse order at the same intervals and carried for the same distance before lapping back. The latest samples have been taken in the centers of the squares formed by the earlier ones. In this manner it has been possible to confine all sampling to an area 25 m. square and thereby to lessen the danger of running into slight



differences in the texture of the soil. After each boring the hole was filled with soil, securely tamped into place, and the spot was covered with a stone. The sampled area is situated where there is nothing to disturb the uniformity of the floodplain surface nor the normal flow of the sheet floods which accompany violent rains.

It must be remembered that under natural conditions there are many factors which affect the uniform entry or loss of soil moisture. Differences in texture from level to level are the most important. In the present case this factor has been of small weight although not entirely negligible. A very fine alluvial soil frequently cracks on drying, but this has not occurred on the area used. The existence of passages made by burrowing insects and rodents may afford quick access to lower levels and also provide channels for evaporation. The decay of a well distributed root system may also afford avenues for movement of water or water vapor in a manner disturbing to the ideal situation in a wholly compact soil. Care has been taken in the present work to eliminate serious sources of error from these causes but there is no way of being certain that they have not been responsible for some of the cases in which individual samples were very different from those adjacent in time and depth.

In order to determine the percentage of error in the method employed, a series of four borings was made on the same day at the four corners of a square meter. In one case a reading was 5% higher than the average of the other three readings at the same depth, involving a maximum difference of 7.3% between the readings. At another depth there was a maximum difference of 4.3%. At the other six levels the maximum difference between readings was less than 2% in each case. A larger series of samples taken over a greater area at the same time would undoubtedly show still greater variation. In view of the long continuation of the borings that was contemplated, with its corrective influence on the data, and with a desire to confine the entire series to as small an area as possible it was decided to make only one boring at each fortnightly interval. The difference of 2% shown at 6 of the 8 levels in the test borings has been regarded as the minimum probable error of the determinations. In the course of the work it has been found that when an aberrant reading appears at a given level on a given date there is commonly a normal reading at the same level on the succeeding date.

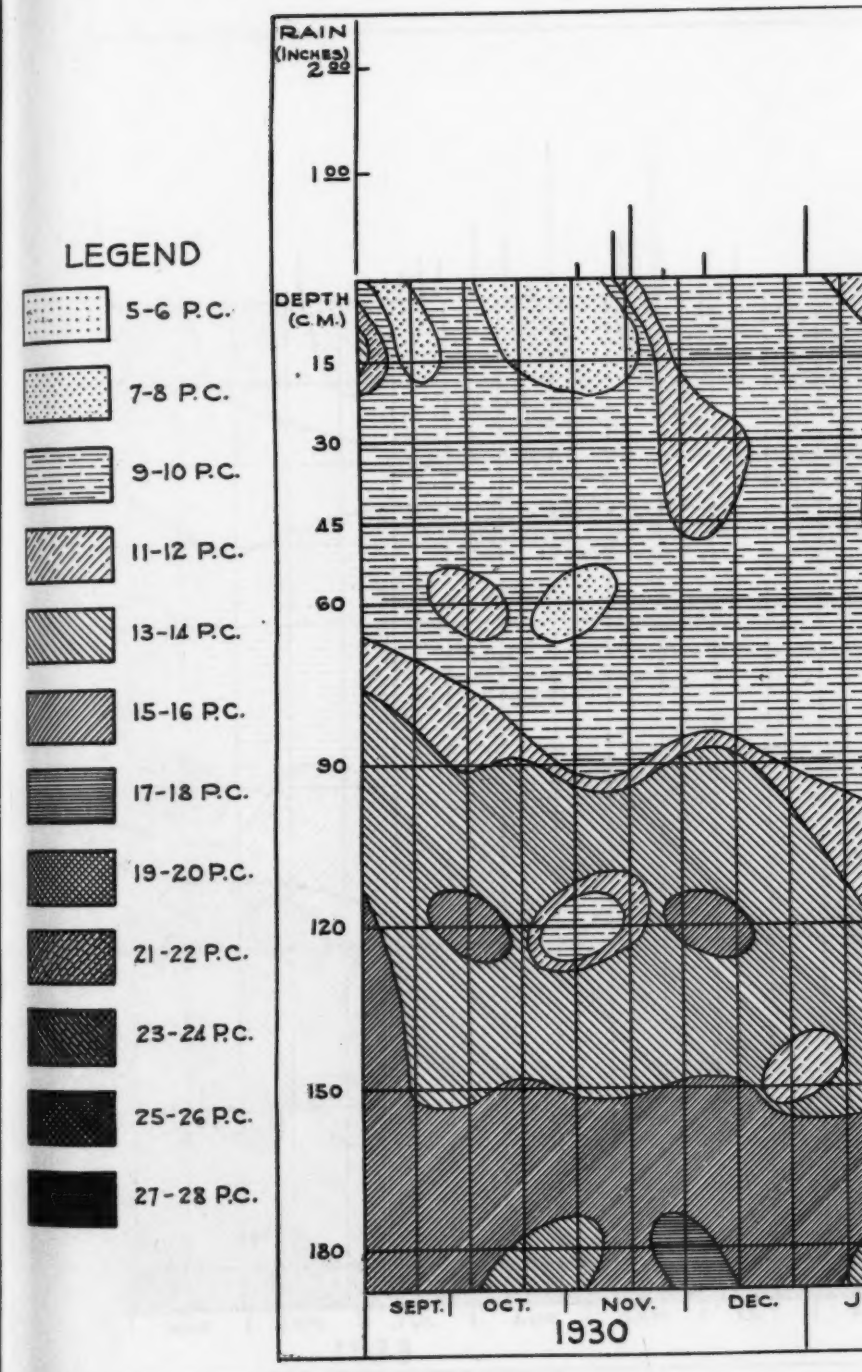
The series of borings in the flood plain was begun on September 9, 1930, and the data for 87 consecutive fortnights to the end of 1933 are given here. The work is being continued in the same place. Fig. 5 has been drawn with a view to showing the amount of moisture at each depth at the time of each reading. For this purpose the original figures have

been grouped into classes by intervals of 2%, all readings from 5.0 to 6.9%, for example, have been grouped, those from 7.0 to 8.9%, and so to the highest class, 27.0 to 28.9%. Outlines have been drawn to embrace all readings of the same class, so as to indicate the time relation of the changes due to penetration and evaporation. The isopleths of soil moisture thus secured have been shaded in order to give a more vivid picture of the march of the moisture supply for plants as it fluctuates from season to season at the various depths.

In drawing Fig. 5 an effort was made to place all of the lines so as to depict the conditions as directly and simply as possible. In no case has a regressive movement of the waves of increasing moisture been indicated, as such an interpretation would naturally be false. In indicating the persistence of a dry zone the appearance of regression is not a misrepresentation. The occurrence of aberrant readings has been indicated by the use of an oval embracing the one or two cases in which samples differed from the adjacent ones. The ovals point down to the right when indicating a higher moisture than the surrounding one and up to the right when indicating a lower one. The aberrant readings may be interpreted as due to the existence of breaks in the continuity of the soil, or as arms extending into the axis of the boring from large bodies of soil in that horizon which have a different moisture content. The aberrant readings at the lowest level may be interpreted as due to the irregularity in the upper limit of the dryer body of soil known to exist at times below 180 cm. In order to give a natural interpretation it was sometimes necessary to carry the indication of a given moisture content over a considerable distance in which no readings of that amount had been taken. This was usually essential to the indication of a proper sequence from one class to the next one of the series.

At the top of the diagram in Fig. 5 the individual falls of rain have been indicated as an aid in interpreting their influence on the moisture changes. It has frequently happened that a heavy rain took place shortly after the soil boring was made, and that much of its effect on the moisture at 15 cm., and possibly even at 30 cm., had disappeared by the time the next boring was made. In the summer particularly a period of 5 to 12 days would result in heavy evaporation from the surface and the rapid return toward the surface of much of the water which had begun to penetrate the soil. After the heavy rain of November 21, 1931, nine days elapsed before the next boring was made, and the maximum wetting was not recorded. This accounts for the fact that the region indicating the highest moisture in the diagram appears to have no connection with surface conditions.

The most obvious features indicated by the diagram of the isopleths of soil moisture are the general tendency toward increase of moisture with in-


LEGEND
5-6 P.C.
7-8 P.C.
9-10 P.C.
11-12 P.C.
13-14 P.C.
15-16 P.C.
17-18 P.C.
19-20 P.C.
21-22 P.C.
23-24 P.C.
25-26 P.C.
27-28 P.C.
RAIN (INCHES)
2.00
1.00
DEPTH (C.M.)
15
30
45
60
90
120
150
180
SEPT.
OCT.
NOV.
DEC.
1930

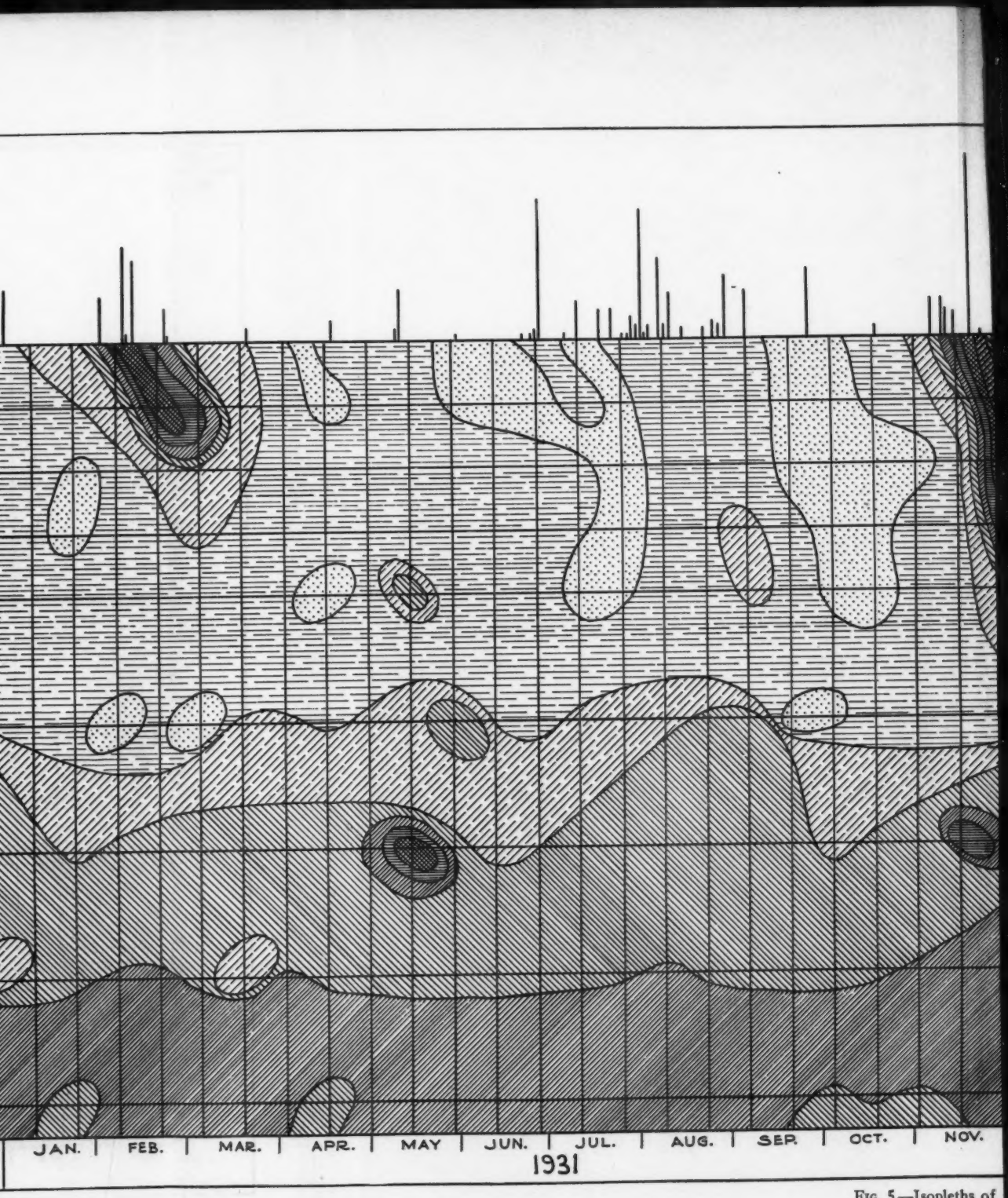
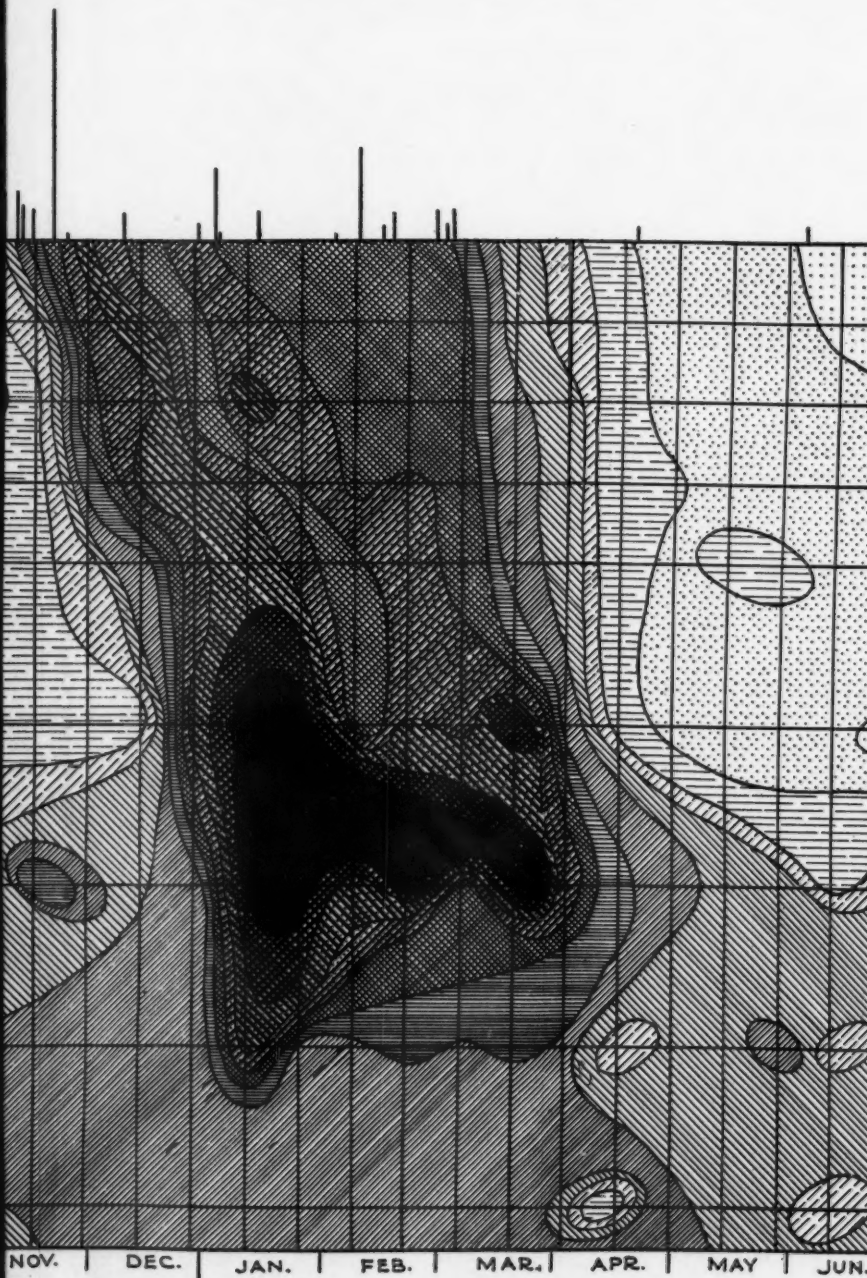
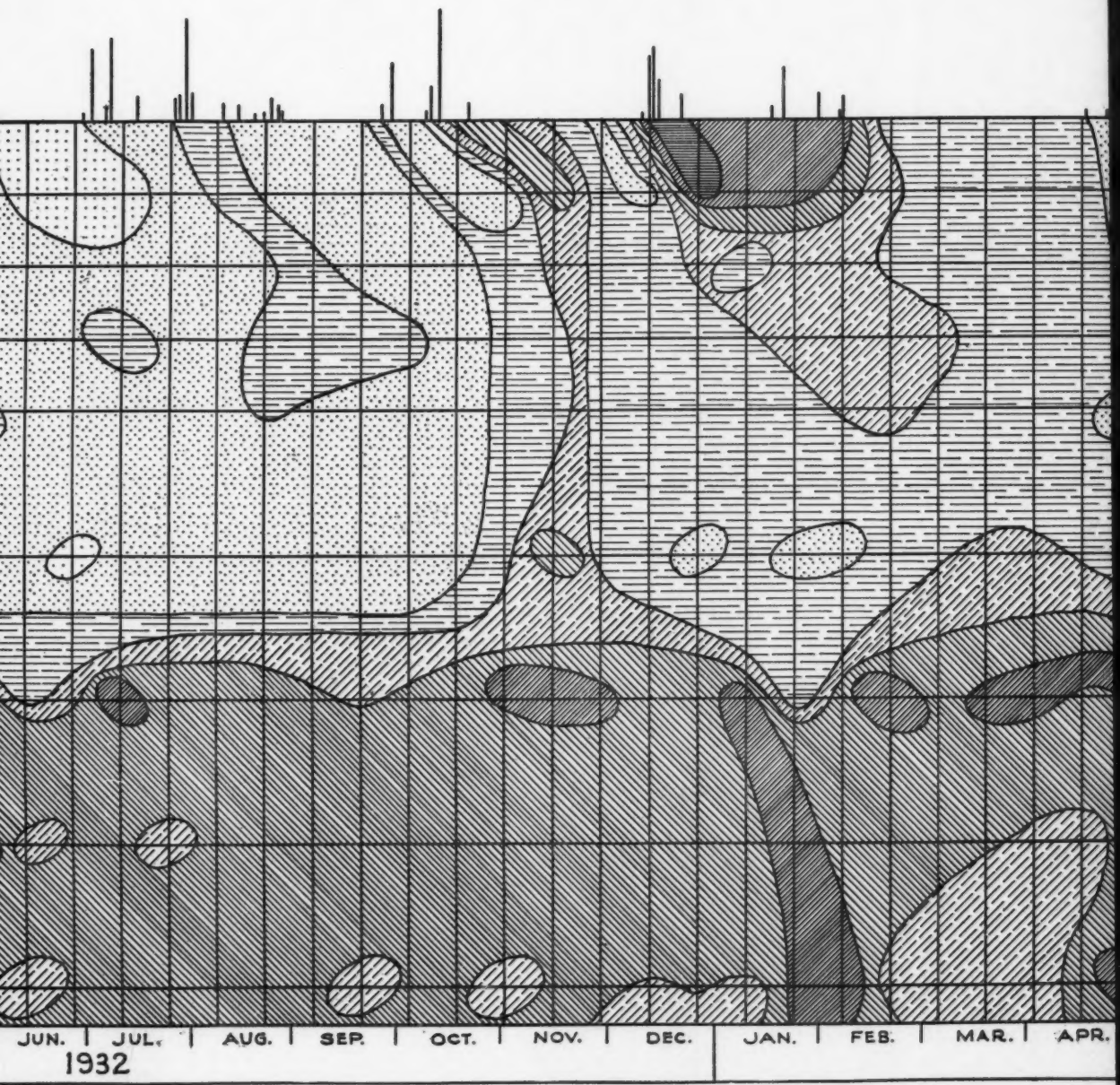


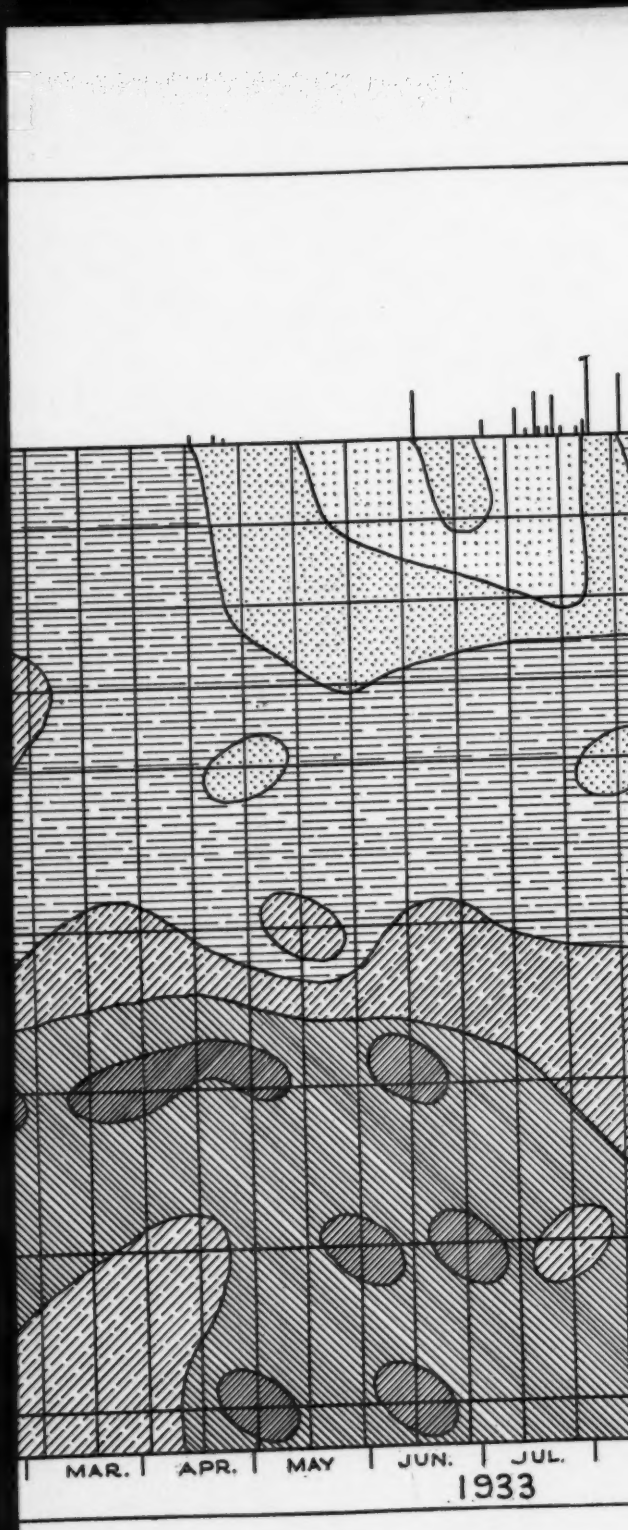
FIG. 5.—Isopleths of



leths of soil moisture at eight depths from September, 1930, to December, 1933, together with



er with rainfall for corresponding period.


MAR.
APR.
MAY
JUN.
JUL.
1933

RAIN
(INCHES)
2.00
1.00
DEPTH
(C.M.)
15
30
45
60
90
120
150
180
AUG.
SEP.
OCT.
NOV.
DEC.

creasing depth and the contrast between the fluctuations at 15, 30 and 45 cm., and the relative constancy at 150 and 180 cm.

The lowest moistures of the series were taken at 15 cm. for three consecutive fortnights at the close of the arid spring of 1932, and for a longer period at the same time in 1933. In the latter case there was a temporary rise at 15 cm. on June 26, due to a rain of .42 in. on June 16. The maximum effect of the arid spring was not felt at 30 cm. until July 24, after 1.93 in. of rain had fallen since the beginning of the summer rains. In 1931 the desiccating influences of May and June exerted their effect to a depth of 60 cm., as shown in the two July readings, taken in the midst of the summer rains. The distribution of the two lowest classes of readings indicates that a moisture of 5–8% is prevalent in the arid spring and the arid autumn, that moistures of 5–6% may be found as deep as 30 cm. and moistures of 7–8% may be found as deep as 90 cm., and may persist at that depth for six months, throughout the summer rains, as happened in 1932.

The highest surface readings were taken in February and March, 1931, from November, 1931, to March, 1932, and in December, 1932, and January, 1933. In the first of these periods the surface moisture reached 19–20%, but the duration of the period of high moisture was not great and the maximum effect of the rains of the winter period was not registered below 45 cm. The second wet period was initiated by a rain of the winter type which was unusually early and exceptionally heavy. Supplemented by frequent rains until February, and aided by the low soil evaporation of the winter months, the moisture from this rain penetrated deeply, reaching 150 cm. from January to March, and having its maximum effect in a moisture of 27–28% at 120 cm. in the same months. The lag due to slow penetration is well shown in the existence of 27–28% of moisture at 120 cm. from January 11 to March 21, as the result of a rain which fell on November 21. The rains of the winter of 1932–33 produced a period of moist soil, in which 17–18% was the highest reading made. The maximum effect of this wet period was not felt below 15 cm. and no immediate effect can be ascribed to it below 60 cm. A number of aberrant readings of 15–16% from January to June, 1933, at depths of 120, 150 and 180 cm. must be ascribed to the effect of the rains of the winter of 1932–33, exerted through avenues at some distance from the sampled area.

It is obvious from an inspection of the isopleths that the winter rains are far more effectual than the summer ones in building up the moisture of the soil. This is due in part to the high runoff that has been shown to characterize the summer rains, and in part to the much more active evaporation from the soil surface at that season. Of the six rainy seasons comprised in the period of observation there was only one which influenced the

moisture below 60 cm., its effect extending to 150 cm. It is evident that much of the water which enters the soil is destined to return by the same path and never to reach the lower levels of higher moisture, where a long capillary journey protects the moisture from possibility of evaporation. There is abundant *a priori* evidence that the moisture of the lower levels is more securely maintained by the existence of a dryer soil above. There is also evidence in the present work that a profound wetting such as the soil received in the winter of 1931–32 may do more to reduce than to increase the moisture of the lower levels. It will be noted that the moisture at 180 cm. stood at 15–16% from September, 1930, until May, 1932, and that the same percentage was sometimes found at 150 cm. Following the heavy wetting of the winter, 1931–32, the moisture at 180 cm. fell to 13–14% and with various aberrancies has stood at that percentage ever since. It is highly probable that this permanent fall was due to the establishment of a better system of capillary films from 180 cm. to the surface than had existed for some time, and that the lower levels of the soil lost water more rapidly through their existence than had been possible under the dry surface conditions of the previous 20 months.

In Fig. 6 are shown graphs (AC) for the yearly average of soil moisture in the alluvial clay for 1931, 1932, and 1933, based on the averages of the 26 annual readings. Each of the curves is extended as a broken line to indicate the percentages found in the one or two annual borings which were made from 180 to 360 cm. These curves indicate that there is a normal tendency toward a sharp rise in the moisture between 90 and 120 cm. The high maximum for 1932 at 120 cm. is due to the heavy rain of 1931, as already described, and is probably an exceptionally high average for that depth. Normally the maximum moisture appears to exist at 210 to 240 cm., and below those depths there was a sharp fall to 360 cm. in 1932 and 1933, and a rise from 300 to 360 cm. in 1931. Owing to the seasonal constancy of the moisture below 150 cm. the data taken below 180 cm. undoubtedly deserve more weight than the infrequency of the borings would indicate. Although three of the four sets of determinations were made in March, when the highest moisture of the year is found, the three curves indicate that there is commonly a fall in the moisture below 240 cm. The water table in the Santa Cruz floodplain lies at a depth of 17 to 20 m., and the soil above it is moistened by capillarity for 1.5 to 2 m. At best there are 11 m. separating the lowest level sampled and the highest level moistened by the water table. Indications make it doubtful if any part of this zone contains more moisture than the zone between 120 and 240 cm. It is still more doubtful if any of the rain falling on the floodplain reaches the ground water by penetrating the soil surface of the plain. It is only the

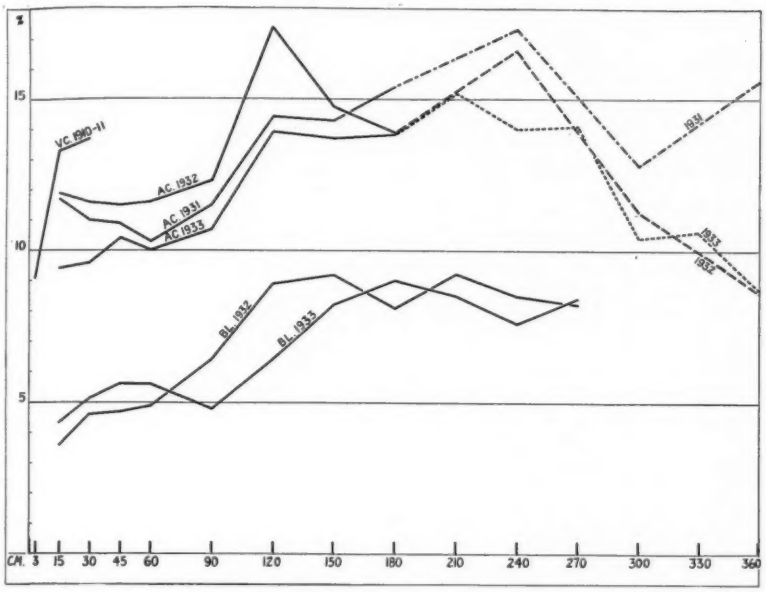


FIG. 6.—Average annual soil moisture at depths indicated in volcanic clay (VC), alluvial clay (AC), and bajada loam (BL).

runoff, reaching the channel of the river, which may contribute to the ground water supply.

It is of some interest to calculate from the moisture data the amount of water held in a cubic meter of soil at the surface and in the second cubic meter. In making such a calculation it is necessary to give double weight to the readings at 90, 120, 150 and 180 cm., owing to the 30 cm. interval between them as contrasted with the 15 cm. interval between the readings nearer the surface. On the basis of the calculated weight of 1380 kilos for a cubic meter of dry alluvial clay, and the average moisture of the first and second meters in the first week of February and the last week of June, the data have been secured which are shown in Table 6. At the time of the highest moisture content the first two meters of soil contained an amount of water equivalent to 21.08 in. of rainfall. With no allowance for runoff, evaporation or penetration to greater depth this was approximately the entire precipitation of the preceding 14 months. In the four months from February to June, 1932, the amount of water in the surface cubic meter fell from 281.5 L. to 95.2 L. This loss of about 10 L. per week was due in part to penetration of water to a deeper level, but the simultaneous

TABLE 6

CALCULATED WATER CONTENT (IN LITERS) OF FIRST AND SECOND METER OF SOIL AT TIME OF FIRST DETERMINATION IN FEBRUARY AND LAST IN JUNE, TOGETHER WITH EQUIVALENTS IN INCHES OF RAINFALL

		1931		1932		1933	
		Feb.	June	Feb.	June	Feb.	June
First meter	Water content	129.7	125.6	281.5	95.2	147.7	140.8
	Rainfall equivalent	5.10	4.94	11.08	3.75	5.81	5.54
Second meter	Water content	212.5	201.5	253.9	186.3	200.1	196.0
	Rainfall equivalent	8.36	7.93	10.00	7.33	7.87	7.72

loss of 67.6 L. by the second cubic meter gives strong indication that most of it was lost by evaporation. The course of the moisture content at 15 cm. from February to June indicates that the rate of evaporation greatly exceeded 10 L. per week per square meter during the latter part of February and early part of March and was far below that amount in May and June. During the relatively dry spring of 1933 the loss of water by the surface cubic meter from February to June was only 6.9 L. and in the second meter 4.1 L. The great contrast between the amounts of evaporation in the spring of 1932 and 1933 corroborates the theory that the thorough moistening of the soil in the former year caused a loss from the lower levels as well as the surface.

The soil moisture determinations made in the bajada loam on the west side of the grounds of the Desert Laboratory are shown in graphs on Fig. 6 (BL). The curve for each year is the average of the determinations made in March and June, at the times of maximum and minimum moisture for the year. The curves for the two years are similar and are both well below the averages for the same depths in the alluvial clay (AC), the average moisture in the bajada soil being only a little more than half the amount in the alluvial clay.

In all sampling in the bajada loam this soil, with many rock fragments, was found to a depth of 60 to 90 cm. Below that level was encountered a thick deposit of soft caliche to the 270 cm. level. The physical properties of this material and its rôle in relation to soil moisture have been discussed by Shreve and Mallery.[1] Although much harder than the soil, the caliche in this locality can be easily broken with a pick. It contains a few stones

[1] Shreve, Forrest and T. D. Mallery. The Relation of Caliche to Desert Plants. *Soil Science*, 35: 99–112 (1933).

and a varying percentage of soil particles, its bulk being chiefly made up of calcium carbonate. Roots were abundant in the soil, particularly in the lowest level just above the caliche, but were infrequent in the caliche. It has been shown in the paper cited that the water holding capacity of caliche is less than that of all soils other than sand, and that its texture makes it more retentive of moisture than most soils. The constancy of the moisture in the bajada localities from 150 to 270 cm. confirms the experimental evidence as to its retentivity. The roots which are spread over its surface and distributed through the favorable regions in it, have a constant but small supply of available water.

When the averages of the March and June readings are compared it is found that they are 5.5% and 2.5%, respectively, at 15 cm. and that they rapidly come to close agreement when the caliche bed is reached, being 8.7% and 8.4%, respectively, at 180 cm.

Livingston[2] has published determinations of moisture at 10 and 20 cm. in the soil of the outwash slopes of Tumamoc Hill, which is somewhat heavier than the bajada loam and underlaid by rock and hard caliche at depths of 20 to 40 cm. His curves show a close agreement between the moisture at the two depths, with maxima of 15 to 18% in the winter (December to February), a sub-maximum of 12 to 13% in the summer, and minima of 2 to 3% in the arid spring and autumn.

Shreve[3] made weekly determinations at a depth of 15 cm. from February to November in a bajada soil somewhat heavier than the loam. The lowest readings were secured in March and June (7.6 and 9.8%, respectively) and the highest in August (14.9%).

All of the available data indicate an annual fluctuation of moisture in the bajada soils which is much smaller than that found in the alluvial clay and also a much lower range of moistures in the former soils than in the latter.

Shreve[4] has also published data on the moisture of the heavy volcanic clay of Tumamoc Hill, based on weekly readings at 3, 15 and 30 cm. for 12 months in 1910–11. The averages for the three depths have been included in Fig. 6 (VC). Owing to the shallow and irregular soil cover on Tumamoc Hill it was not possible to get a continuous series of samples at a greater depth. There are, however, pockets and veins of soil in which

[2] Livingston, B. E. Relation of Soil Moisture to Vegetation. *Bot. Gaz.*, 50: 241–256 (1910).

[3] Shreve, Forrest. Physical Conditions in Sun and Shade. *Ecology*, 12: 96–104 (1931).

[4] Shreve, Forrest. Rainfall as a Determinant of Soil Moisture. *The Plant World*, 17: 9–26 (1914).

moisture is undoubtedly carried at percentages higher than those found at 30 cm. The averages of 15 and 30 cm. are higher than the averages for the same depths in alluvial clay and far higher than those in the bajada loam.

Any attempt to determine the relation of soil moisture to plant life requires consideration of the texture or mechanical composition of the soil. When data on several soils are compared, and the percentages of moisture are based on dry weight, it becomes particularly important to translate the data into terms of the actual availability of the moisture to plants.

In Table 7 are shown figures for the mechanical composition of the three soils in which moisture data were obtained. It will be noted that

TABLE 7

MECHANICAL COMPOSITION OF SOILS IN WHICH MOISTURE DETERMINATIONS WERE MADE. DIAMETERS IN MM. DATA IN PERCENTAGES

Soil	Depth	2.0–1.0	1.0–.5	.5–.25	.25–.1	.1–.05	.05–.005	.005–0
Alluvial clay	15 cm.	1.0	0.9	0.9	5.5	13.5	45.5	32.8
Alluvial clay	1 m.	0.1	0.1	0.1	2.9	7.8	34.6	54.4
Alluvial clay	3 m.	0.2	0.2	0.2	1.8	14.5	48.0	35.1
Bajada loam	15 cm.	1.3	15.4	9.6	14.8	14.0	24.8	20.2
Volcanic clay	15 cm.	1.2	1.3	0.8	3.3	7.0	27.9	58.4

there is a strong preponderance of the finest class of particles in the alluvial clay and volcanic clay, with far greater percentages of the coarser classes in the bajada loam. For each of the soils determinations have been made of their water-holding capacity, which is the maximum percentage on dry weight that they will hold against gravity. The capacity for alluvial clay is 50.4%, for volcanic clay 48.2%, for bajada loam 32.0%. There is much to be said in favor of a system of expressing the amount of moisture in a soil on a basis of the water holding capacity as 100%. When the bajada loam has 16% it is half saturated and when volcanic clay has 16% it is only one third saturated.

The familiar investigations of Briggs and Shantz[5] constituted an effort to derive purely physical soil constants that would express accurately the availability of water to plants in different soils. The moisture equivalent, or percentage of water retained against a pull of 1000 times gravity, is an expression of the strong retention of water against the pull of absorbing roots. In Table 8 it will be seen that the moisture equivalent of volcanic

[5] Briggs, L. J., and H. L. Shantz. The Water Requirement of Plants. *Bur. Plant Ind. Bull.*, 284 (1913).

TABLE 8

MOISTURE EQUIVALENTS AND CALCULATED WILTING COEFFICIENTS OF ALLUVIAL CLAY AND VOLCANIC CLAY IN WHICH MOISTURE DETERMINATIONS WERE MADE, AND IN BAJADA LOAM OF SIMILAR CHARACTER FROM OTHER LOCALITIES

Soil	Depth	Moisture equivalent	Wilting coefficient
Alluvial clay	15 cm.	23.88	12.98
Alluvial clay	15 cm.	26.54	14.42
Alluvial clay	3 m.	21.00	11.41
Bajada loam	15 cm.	18.51	10.06
Bajada loam	15 cm.	12.16	6.61
Bajada loam	15 cm.	12.00	6.52
Volcanic clay	15 cm.	30.09	16.35

clay is 30.09, which is high for any soil. For alluvial clay it ranges from 21.00 to 26.54, while for bajada loam it is 12.00 to 18.51.

The authors cited have given experimental evidence that the moisture equivalent bears a nearly constant relation to the wilting coefficient, or percentage of soil moisture which is not available to plants. In Table 8 are given the calculated wilting coefficients for seven samples of the three soils, those for bajada loam being taken at three localities near the Desert Laboratory grounds. Using the average value for each soil these figures indicate that plants will wilt in alluvial clay when its moisture falls below 12.9%, in volcanic clay when it falls below 16.3%, and in bajada loam below 7.7%.

The wilting coefficient is a physical constant which, in many cases and under certain conditions, serves to express a limiting condition for plant activity. It appears, however, from several considerations, not to be a precise expression of the balance between environment and plant. In the case of the present work it will be noted that the course of the soil moisture down to a depth of 90 cm. is often well below the wilting coefficient for many months, although plants are active during part of this time.

The natural vegetation of the alluvial clay is a fairly well closed forest of mesquite (*Prosopis velutina*), reaching a height of 6 to 12 meters. This is a type of vegetation with high water requirement. The natural vegetation of the volcanic clay is a rather open mixture of many types of plants in which the palo verde (*Cercidium microphyllum*), acacia (*Acacia constricta*), creosote bush (*Larrea tridentata*), desert hackberry (*Celtis pallida*) and several species of cacti are prominent. These are plants of smaller size and less water requirement than the mesquite. On the bajada loam the

vegetation is a very open stand of creosote bush, usually with few other associated plants of large size. This is a community of small water requirement. The depth of the alluvial clay places a large store of water at the disposal of the mesquite, the roots of which sometimes penetrate to a depth of 10 meters. The shallowness of the volcanic clay limits the extent of the good moisture supply available to the plants of that soil. The low range of moistures in the bajada loam, together with the almost universal occurrence of caliche in the outwash of volcanic hills, renders the conditions severe for plants and permits only the open occurrence of the most drought-resistant shrub of the region. The march of soil moisture conditions seems, therefore, to be one of the most important conditions differentiating the vegetation in a region in which securing an adequate water supply is the most immediate problem of all plants.

Desert Laboratory of the Carnegie Institution of Washington.
April, 1934.

Pattern of Occupance in the Maracaibo Basin

ROBT. S. PLATT

For this reconnaissance study the Maracaibo Basin was traversed from the northwestern to the southeastern margin, and special attention was directed to the pattern of occupance in two small areas (Fig. 1). These two spots form an almost infinitesimal part of the basin area and are not typical of all of it. But they seem as typical as any two spots that might have been selected. Moreover, they represent not only two kinds of occupance now present at different places, but also two stages in a sequence of occupance—one old, the other new.

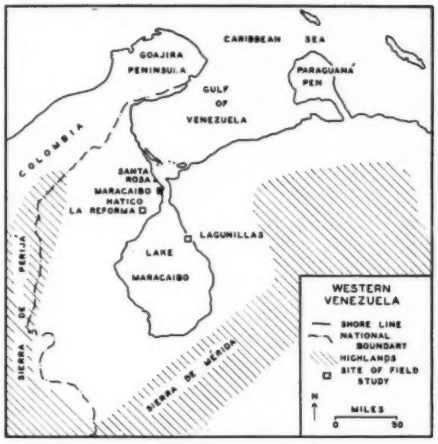


FIG. 1

The field was entered from Colombia by airplane over the Sierra de Perijá. The region is too large to be viewed entirely from one point, but from the air the basin-like form seems perceptible—the rim of mountains, the belt of lowlands and the central body of water. Dense forest on the mountain slopes, broken only by streams, gives way in the lowland to scrub woods, broken by openings or clearings increasingly numerous near the lake (Fig. 2).

HATICO LA REFORMA

These openings indicate *haticos,* little ranches, each with an area partly cleared, a patch of cultivation, a small house, and a water hole. In this vicinity is the first of the spots studied on the ground. Hatico La Reforma is inland from the lake, about 10 miles southwest of Maracaibo (Fig. 1). It is accessible by a cart road quite unimproved but adequate for the small

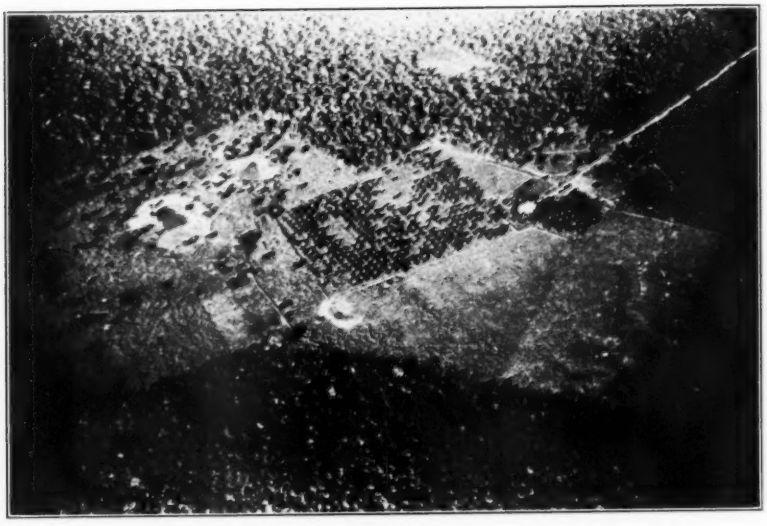


FIG. 2.

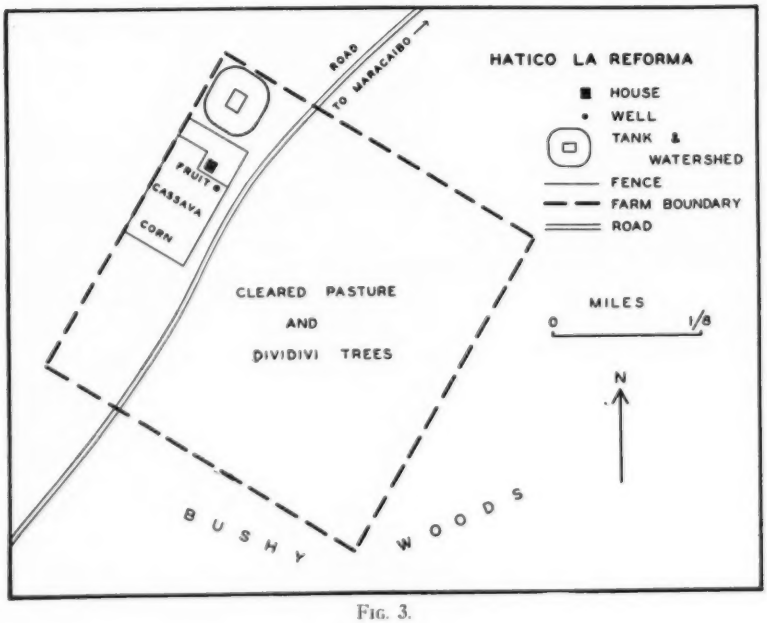

ROAD
TO MARACAIBO
HATICO LA REFORMA
HOUSE
WELL
TANK &
WATERSHED
FENCE
FARM BOUNDARY
ROAD
FRUIT
CASSAVA
CORN
CLEARED PASTURE
AND
DIVIDIVI TREES
MILES
0
1/8
N
BUSHY WOODS

FIG. 3.

FIG. 2.—Air view of a ranch clearing in scrub woods about ten miles west of Maracaibo. Water holes in partly cleared pasture at the left; a road leading to the house at the right; and in the center a grove of coconut palms, a feature not present in Hatico La Reforma.

amount of traffic over it in the undulating sparsely wooded plain. The district has aspects of semi-aridity consistent with an annual rainfall of about 20 inches falling in a season of 7 months, average temperature of over 80° F. for every month, and rapid drainage through the sandy soils of partially consolidated coastal plain sediments. This combination does not mean desolation necessarily. Mistletoe is as plentiful as cactus, and live animals are more in evidence than dead ones.

The *hatico* is a ranch of 62 acres (Fig. 3). Its clearing is surrounded by bushy woods but the property adjoins that of other ranches. Beside the the road which cuts across the property is a farmyard or corral enclosed by a picket fence (Fig. 4). In this one-acre enclosure is the only building, a

FIG. 4.—Dividivi trees and goats in pasture, Hatico La Reforma. In the background the fenced enclosures in which are visible the two-compartment house at the right, papaya trees in the center, and mango tree at the left.

one-story stucco dwelling and storehouse formed of two compartments. Adjoining the farmyard is a similarly enclosed 4-acre field, the agricultural part of the establishment. In it are irregular patches of cassava, corn, and

FIG. 5.—Water hole of Hatico La Reforma.

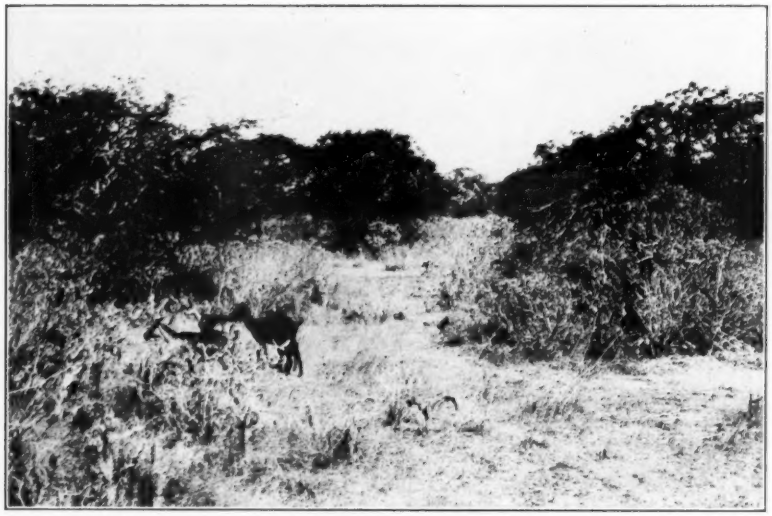


FIG. 6.—Goats in bushy woods on the border of Hatico La Reforma.

beans. In the corner near the house is a deep dug well, and about this are a few fruit trees and nursery beds. The well is for domestic water supply. Irrigation is limited to watering young trees and nursery plants by hand in the dry season. Plantains and papayas and a single mature mango tree produce well; the field crops depending on precipitation yield fairly well in years when the rainy season does not fail. The land used for cultivation is not apparently different from its surroundings in soil or surface, and is distinguished only by its location near the house, which in turn is located near the road.

On the other side of the house, outside of the enclosure, is a water tank, a square hole dug in the ground and surrounded by a broad embankment forming a basin to gather rain water (Fig. 5). In the rainy season the tank receives enough water to last through the year. This is the watering place for livestock.

The rest of the property is pasture land, most of it cleared of bushes and having a park-like aspect with an open stand of dividivi trees and a sparse growth of grass (Fig. 4). The property is not fenced. Animals wander out into the bushy woods surrounding the cleared land (Fig. 6), but generally return to their own water hole. Probably a few are lost; exact numbers are not known. There are about 50 goats and kids, 2 cows, 1 burro and a few pigs and fowls.

Goats are the principal product of the *hatico*. They do not give a significant amount of milk, and it is for their skins that some goats and kids are driven occasionally to Maracaibo to be sold.

A second cash product is dividivi, pods of the prevalent leguminous tree of the area, valuable for their content of tannic acid. These are gathered in the dry season by all the members of the household and stored until sold to a dealer and carried to Maracaibo.

The *hatico* is an old establishment. The owner is a Venezuelan of Spanish descent with some Indian blood. His family is large, having somewhat the aspect of a harem (Fig. 7). Apparently these people find the *hatico* sufficient in size and in attached resources for their support. The pattern of the ranch seems to be such as to attain this objective.

The family is not isolated nor peculiar. There are neighbors within a mile, and the establishment is like others in the vicinity. Elsewhere in the region there are differences including less rainfall in the northern, and greater rainfall in the southern part of the basin; but signs of semi-aridity are widespread, having been observed under similar edaphic conditions at the tip of the Goajira Peninsula a hundred miles to the north and at the base of the Andes a hundred miles to the south (Fig. 1).

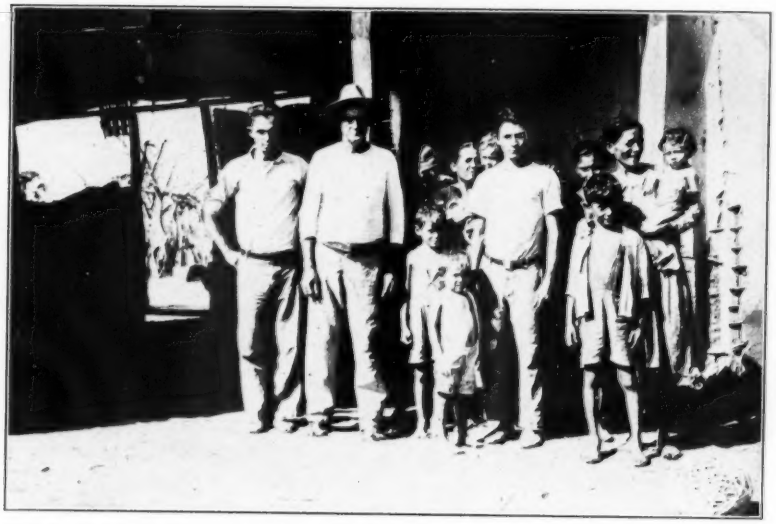


FIG. 7.—The owner and his family in the patio between the compartments of their house, Hatico La Reforma.

FIG. 8.—Water front of the village of Santa Rosa. Coconut palms at the left; fishing boat in the background at the right.

SANTA ROSA VILLAGE

In the vicinity of the *hatico* the most striking contrast in landscape is seen at the lake shore. The second field study site is on the shore at Lagunillas, but before passing across the lake to this site, mention may be made of another lake shore place as a transition from the *hatico* to Lagunillas. At the shore village of Santa Rosa rural occupance is nearly as simple as in the *hatico* area though households are more concentrated and resources are different (Fig. 8). Goats and dividivi are almost if not quite supplanted by fish and coconuts.

Santa Rosa is older than the *hatico*. It may even have been one of the lake villages which gave the name of Venezuela, Little Venice, to the country, at the time of Spanish discovery.

Such a building site has some disadvantages. For example, near the outlet the lake water is brackish and fresh water is obtained only at some distance on shore from holes dug in sand. But in general this distinctive form of settlement is one befitting local circumstances, here where the shore is low and overgrown, the water calm and shallow, and where simple pile construction provides a more healthful home on water than on land, with relative security from insect and other enemies.

LAGUNILLAS AND VICINITY

Across the lake at Lagunillas, a similar village arrangement appears (Fig. 9). But in this vicinity there has been a radical change in occupance.

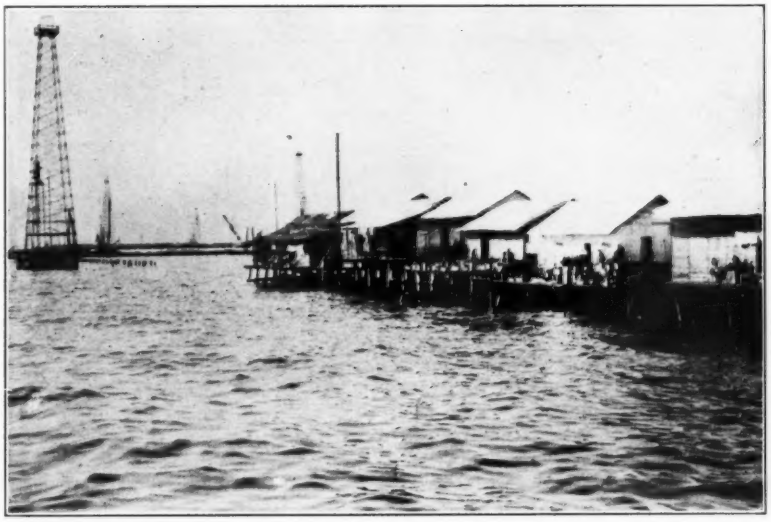


FIG. 9.—Water front of the village of Lagunillas. Oil well at the left.

Petroleum has diverted attention from the old foundations and modes of human activity. Coconuts and dividivi remain only as part of the scenery —at least so they appear to outsiders if not to the indigenes. Lagunillas is the site of the greatest oil field in Latin America (Fig. 10), producing 50

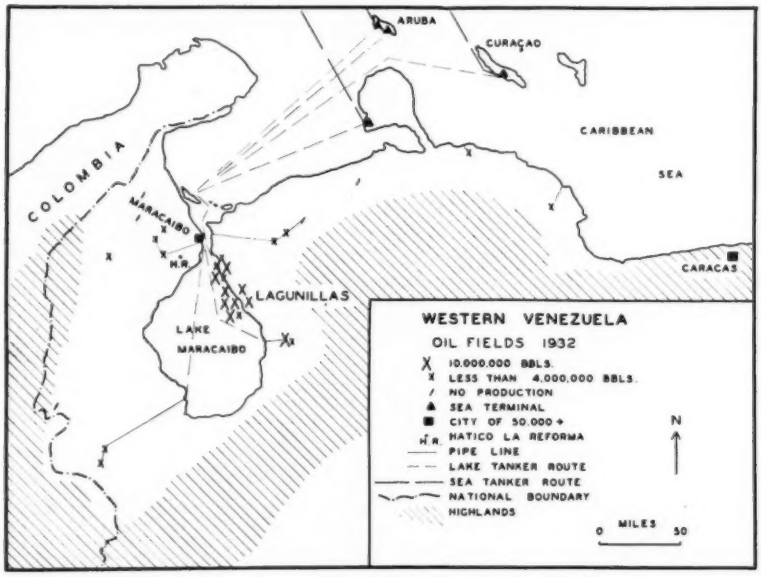


FIG. 10.[1]

per cent of the Venezuelan output and 4 per cent of the world output in 1932.

The village is not old in its present form. It has been swept by fire twice since the arrival of oil in 1926. Oil is spread on the water around and below the village, hazardous and unsightly though sanitary.

Otherwise the settlement is less changed than might have been expected. Lagunillas is still a village of shacks, fairly detached, if not unconscious of the phenomenon which is growing and buzzing around it, an alien phenomenon like an excrescence drawing in previously unknown people and things from the outside world, and drawing up previously unknown resources from below.

The imported personnel of the oil field, bringing its own equipment, has

[1] This map is based on maps and tables in "Who's Who in Venezuela," Maracaibo, 1932. Acknowledgments are due to the Editor of Who's Who, Mr. C. C. McDermond of Maracaibo, for valuable cooperation in the field.

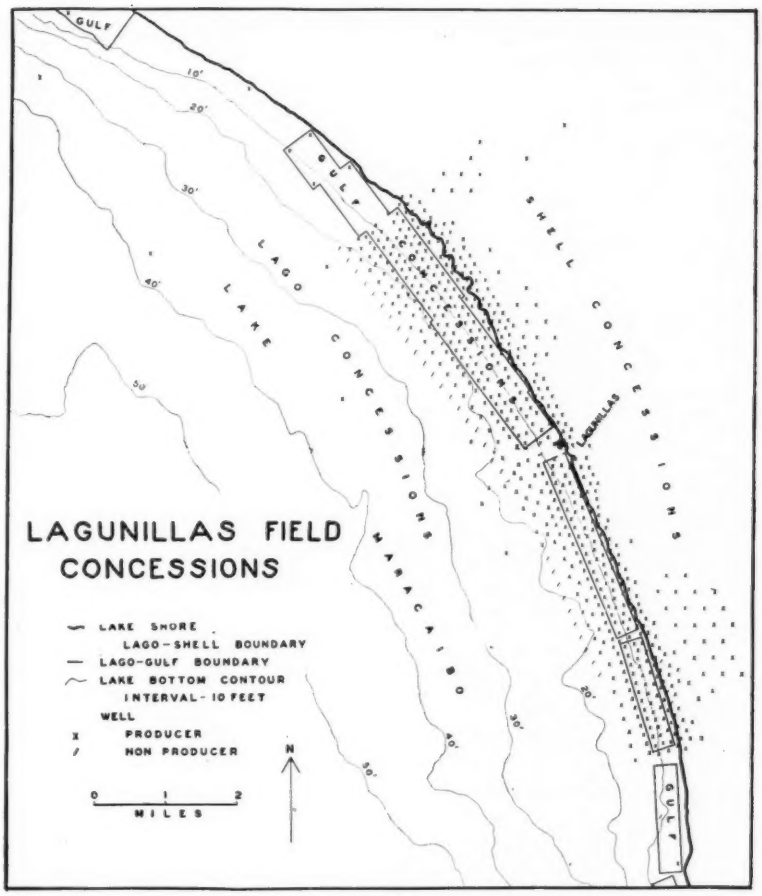


FIG. 11.[2]

applied a foreign technique to local problems and developed in a standardized manner a functional pattern befitting the local situation (Fig. 11). The pattern reflects local conditions at the earth's surface and below and above.

The oil wells themselves are basic items in the pattern. There are 622

[2] This and the other oil field maps are based on materials provided by the Lago Petroleum Corporation. Acknowledgments are due to the officials of the Lago Petroleum Corporation and the Standard Oil Company of New Jersey not only for these maps but also for generous hospitality and assistance in the field.

of them, of which 612 are productive and 10 are abandoned. Most of them are distributed evenly or almost evenly in a sharply defined elongated area. A few are scattered beyond the central group.

Subsurface structure is reflected in this distribution. The oil occurs at depths of from 3000 to 5000 feet in a minor anticline of Miocene sand within the Maracaibo Basin geosyncline. The wells are clustered in a proven area. Their spacing is calculated to extract the resource efficiently. A normal distance of 1000 feet apart is increased where the oil sand is thin and lean, and decreased where it is thick and rich. The scattered outlying wells are exploratory, in areas not drilled up for production.

The cluster of wells does not coincide with the anticline in from and orientation, although there is a rough correspondence. The cluster follows more precisely the trend of the lake shore in a curve averaging N. 30° W. This happens to lie approximately but not exactly over the axis of the anticline which trends N. 20° W.

This orientation of wells in accordance with a surface form rather than subsurface structure is not evidence of direct relationship between the location of the wells and the nature of the surface. The wells are spaced systematically without regard for any differences in land or water. No natural feature either favors or interferes with the placement of a well. But indirectly surface features are important in the location of wells because these features were used in defining concessions. Due to familiar differences between land and water in surface occupance, and perhaps also due to a progressive appreciation of oil drilling possibilities in water as well as on land, separate concessions were granted: first all the land to the water's edge; secondly, certain blocked out areas in the lake near the shore; and thirdly, all the rest of the lake.

Separate petroleum interests have acquired these concessions, and now the opening of the field has been marked by offset drilling along concession margins. The Dutch Shell company controls all of the land and has drilled two rows of wells along the shore. The Gulf Oil Company of Pennsylvania controls the rectangular blocks near shore in the lake, and has drilled two rows of wells along each side of these concessions. Since these are narrow strips, the offset drilling has almost covered them with wells. Finally the Lago company, subsidiary of the Standard Oil Company of New Jersey, controls all the rest of the lake, and has drilled two rows of wells outside of the concessions of the Gulf company in the lake, and irregular rows of wells in shoestring areas left over between the offshore blocks of the Gulf company and the land concessions of the Shell.

That the present pattern is only a preliminary stage is indicated by the fact that exploratory wells have proven successful in the Shell concession

inland 2½ miles to an apparent limit of production, and in the Lago lake bed concessions out into the lake 2½ miles, not to a limit of possible production but to a water depth of 35 feet restricting operations for the time being. Along the shore the area of large production extends about 8 miles.

The competitive development of the field involves much more than the distribution of wells. Each competitor has its own camp and tank farms, triplicating each sort of building (Fig. 12). Since these are on shore they

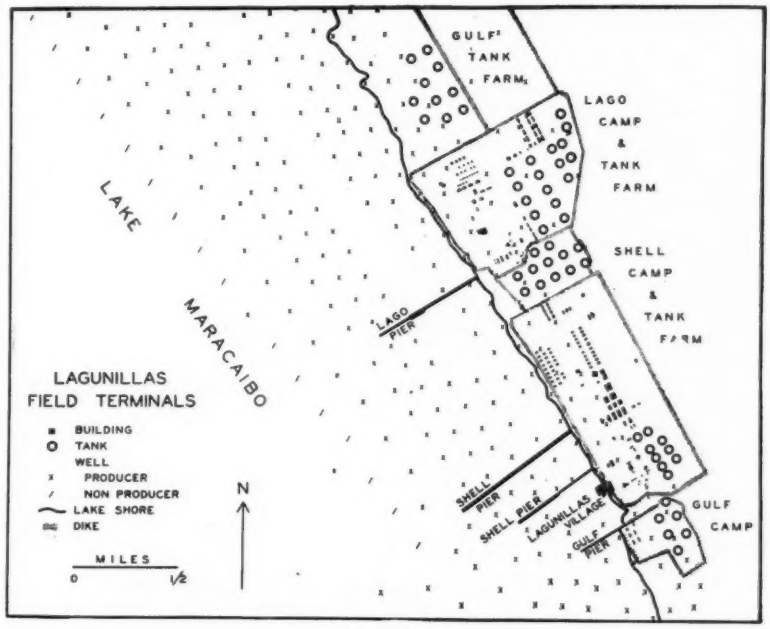


FIG. 12.

are all necessarily in the area of Shell concessions, and Shell wells are distributed not only through their own camp but also through the Lago and Gulf camps. Subsurface rights are separate from surface ownership.

The whole pattern of field equipment fits into these local circumstances of production area, concession boundaries, and land and water. Some of the complexities of the pattern are illustrated by the Lago system of wells, lines, and focal points (Figs. 13 and 14).

There are 199 Lago wells. All that have been completed are producers. Most of them flow naturally; a few are on gas lift; none is pumped. Pipes from individual wells focus on 27 flow stations in the lake, each centrally

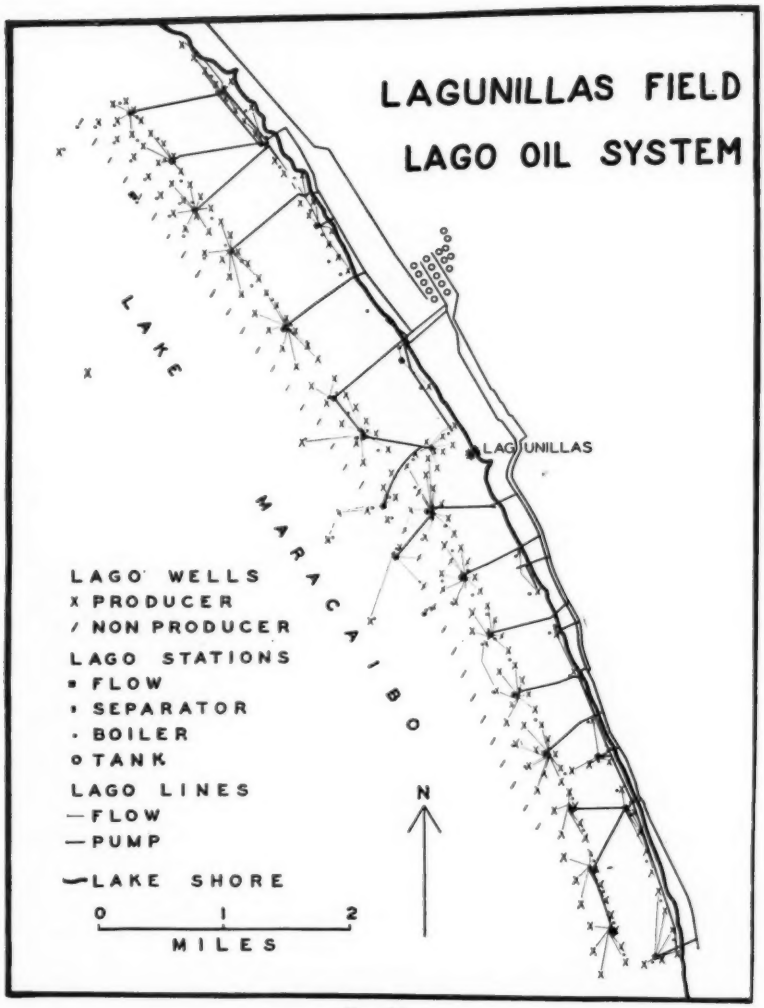


FIG. 13.

located with reference to about 8 wells. The arrangement is symmetrical in the lake bed area, but cramped near shore between Gulf and Shell concessions. From the flow stations oil is pumped ashore in trunk lines to the tank farm for storage and ultimately to the pier for shipment by tanker.

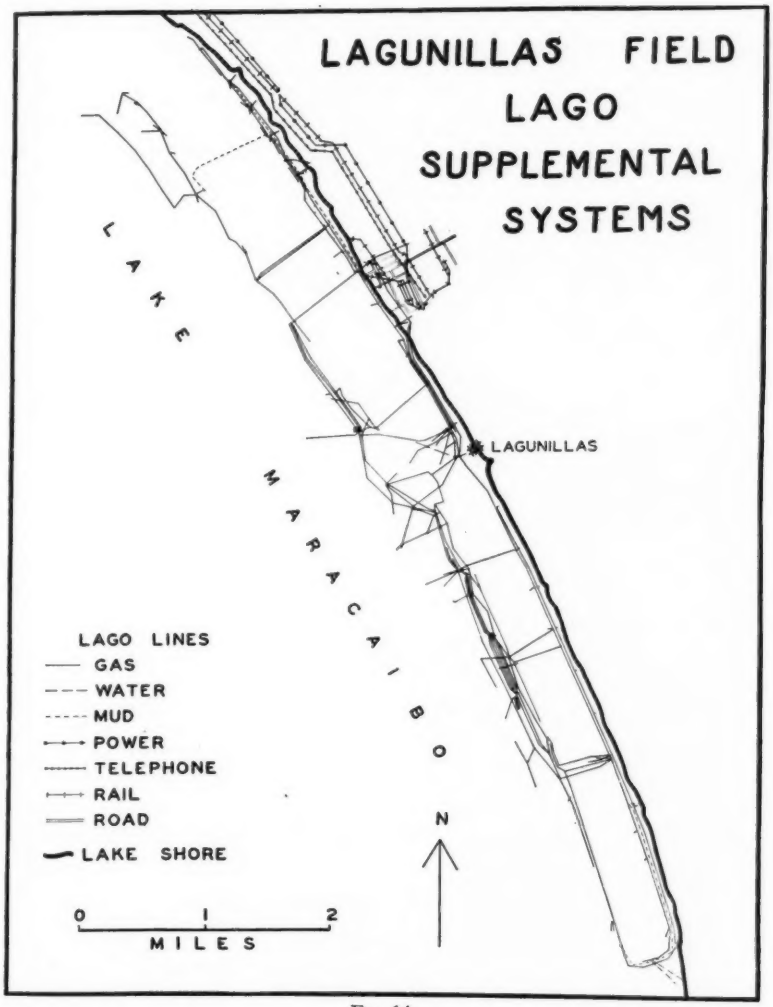


FIG. 14.

Many of the flow stations are accompanied by gas separators, distributed at these primary focal points to relieve the oil of its gas content before pumping it ashore. The gas is piped separately to an absorption plant of which there are two in the lake (Fig. 15), each centrally located with reference to about half of the separators. Here the gasolene content

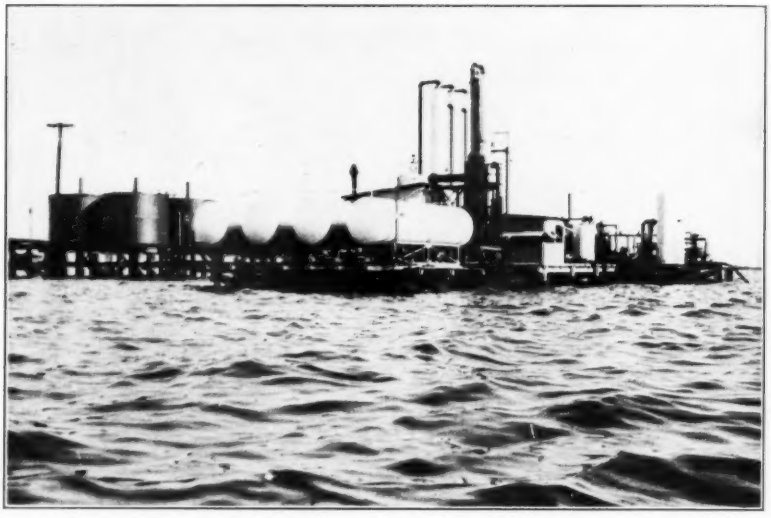


FIG. 15.—A Lago absorption plant in the lake. The shore barely visible in the distance at the right.

of the gas is recovered and dry gas is pumped back through a system of pipes into the wells that are on gas lift (Fig. 14). Since the Lago company has a surplus of gas for this purpose at Lagunillas some of it is piped to an older field twenty miles to the north, where the supply of gas for Lago wells is insufficient.

Boiler stations also are distributed in the lake to supply power according to the needs of the several establishments. Placement of the various focal facilities in the lake minimizes transportation mileage by consolidation of pipe lines and avoidance of return movement.

The establishments placed on land are only those of larger space requirements, of greater focal range for the whole field, or of dependence on land resources. Such are: housing facilities for the personnel, offices and workshops, storage tanks and yards, and mud pits.

These establishments are served by appropriately localized lines of transportation and communication: water pipes from the lake, railway and telephone connections with the older field to the north, a power line from a central plant, and in camp a small, dense network of roads, tracks, pipes and wires.

The complexity of the pattern is multiplied when to the Lago network of lines and focal facilities is added the equally complete networks of the

other companies, of the Gulf along the border of the lake and on land, and of the Shell entirely on land.

The position of the Shell on land has a suggestion of superiority in comparison with the Gulf company operating in water to a depth of 15 feet and the Lago to greater depths. The order of concessions implies as much.

But as a matter of fact the contrary seems to be true. Shell operations on land involve the clearing of woods and building of roads. On well drained land the vegetation is not dense, but much of the area is swampy and covered with a tropical tangle ordinarily called jungle. At best, mobility is not easily attained. Conditions of work include such adverse factors as ants, mosquitoes, and other pests.

The Gulf avoids these difficulties and is faced only with the lesser problems of working on bridges or in shallow draft boats. The Lago enjoys even better conditions with most of its wells in water deep enough for free use of boats (Fig. 16). The lake is generally calm and although boat work

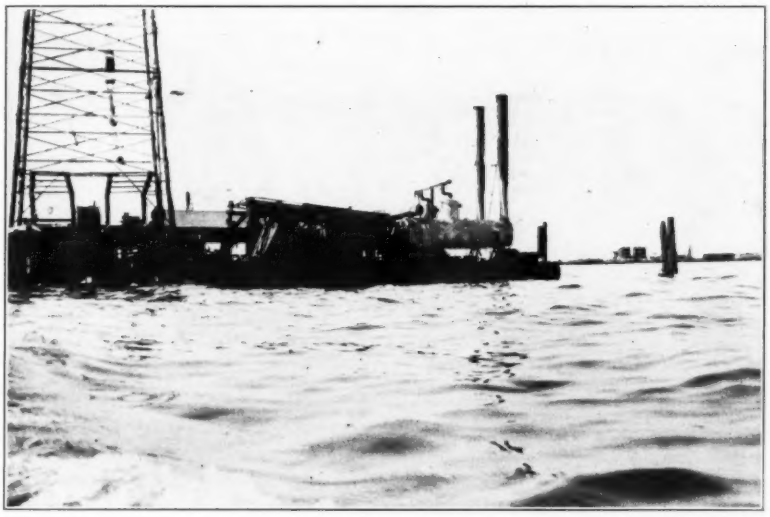


FIG. 16.—Barge at work on a Lago well.

is somewhat slow, it is economical. Well platforms and other permanent structures are built on concrete piling. Thus conditions which favored the lake villages of Little Venice seem to be reflected again in the oil field.

Working conditions are not the chief Lago advantage. A higher average production from wells in the lake bed concession is of more importance.

The Lago company produces half of the field output from less than a third of the active wells.

Meanwhile another difficulty has appeared to handicap land operations. Rapid local subsidence is causing the flooding of land by lake water along the shore (Fig. 17), and by streams on the landward side of the field. The

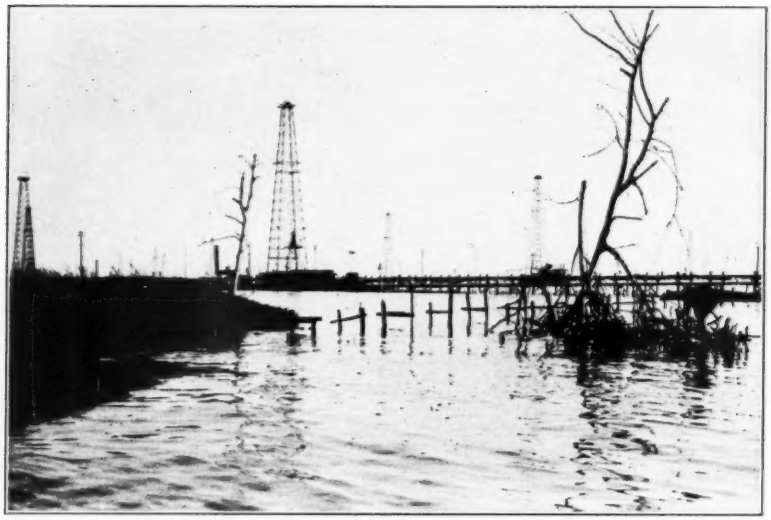


FIG. 17.—Land recently submerged along shore near the Lago camp.

camps, on low land, were already partly protected by dikes, but these are becoming inadequate, and improvement and extension are needed. The Shell company is the chief sufferer, although both the Gulf and the Lago are affected by reason of their camps and by reason of the sinking of their lake platforms. The sinking is limited to the area of the field and is attributed to the extraction of petroleum.

The oil industry is blamed for another natural—or should it be called "artificial"?—phenomenon, an unusual frequency and violence of local thunderstorms since the development of the field. This is attributed to the discharge of gas into the atmosphere.

Details need not be multiplied to illustrate further the complexity of the field pattern and of its functional activity. In general the development of the district is relatively simple; people and things have arrived and fixed themselves upon the area for the exploitation of a single resource, and from the area a single commodity flows out. The crude oil product is shipped

by lake tankers to Maracaibo for clearance, and at high tide out over the bar with a draft limit of 11 feet to the deep water terminals (Fig. 10) of the Gulf company on the Paraguaná Peninsula, the Shell refinery at Curaçao, and the Lago refinery at Aruba, for shipment beyond in ocean tankers or distribution in finished form to world markets.

To pass from these snapshots of the oil field and the *hatico* into generalizations on the Maracaibo region is not within the scope of this study. While regional implications of this reconnaissance are immediately evident, complete regional interpretation waits upon the cumulative results of work carried on along this and other lines of attack by various geographers.

University of Chicago,
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